NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

PARTIAL BAND JAMMING AGAINST 802.16A

by

Daniel P. Zastrow

June 2007

Thesis Advisor:	Tri T. Ha
Thesis Co-Advisor:	Frank Kragh

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2007	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Partial Band Jamming Against 802.16a			**5. FUNDING NUMBERS**
6. AUTHOR(S) Daniel P. Zastrow			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

The IEEE 802.16a standard provides for Broadband Wireless Access (BWA) for the global deployment of broadband Wireless Metropolitan Area Networks (WMANs). Commercially known as Wi-Max, the standard aims to provide large amounts of wireless data over long distances, in a cellular type structure with base stations and subscriber stations. The standard uses Orthogonal Frequency Division Multiplexing (OFDM) which allows the transmission of high data rates in severe channel conditions without complex filters. This thesis tested the performance of a developed partial band jamming algorithm on a modified 802.16a standard. The partial band jamming was applied to 1/8, ¼ and ½ of the total subcarriers. Additionally, both intentional and unintentional interference were added to the signal. The modified code repeated the signal 48, 96, or 192 times and recombined the data using Maximal Ratio Combining. This thesis explored the potential for performance gains by reducing the data rate with a repetition code.. The evaluation was performed in MATLAB®.

14. SUBJECT TERMS IEEE 802.16a, WMAN, OFDM, OFDMA, BWA, Wi-MAX, Multipath, Interference, Maximal Ratio Combining			**15. NUMBER OF PAGES** 89
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

PARTIAL BAND JAMMING AGAINST 802.16A

Daniel P. Zastrow
Ensign, United States Navy
B.S., United States Naval Academy, 2006

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 2007

Author: Daniel P. Zastrow

Approved by: Tri Ha
Thesis Advisor

Frank Kragh
Co-Advisor

Jeffrey B. Knorr
Chairman, Department of Electrical and Computer Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The IEEE 802.16a standard provides for Broadband Wireless Access (BWA) for the global deployment of broadband Wireless Metropolitan Area Networks (WMANs). Commercially known as Wi-Max, the standard aims to provide large amounts of wireless data over long distances, in a cellular type structure with base stations and subscriber stations. The standard uses Orthogonal Frequency Division Multiplexing (OFDM) which allows the transmission of high data rates in severe channel conditions without complex filters. This thesis tested the performance of a developed partial band jamming algorithm on a modified 802.16a standard. The partial band jamming was applied to 1/8, ¼ and ½ of the total subcarriers. Additionally, both intentional and unintentional interference were added to the signal. The modified code repeated the signal 48, 96, or 192 times and recombined the data using Maximal Ratio Combining. This thesis explored the potential for performance gains by reducing the data rate with a repetition code. The evaluation was performed in MATLAB®.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I. INTRODUCTION....1
A. BACKGROUND....1
B. OBJECTIVE....1
C. RELATED WORK....1
D. THESIS ORGANIZATION....2

II. BACKGROUND....3
A. IEEE 802.16A OVERVIEW....3
1. System Architecture Overview....4
2. The 802.16 MAC Layer....5
3. The 802.16 PHY Layer....7
a. Wireless Man-SCa....8
b. Wireless Man – OFDM....9
c. Wireless MAN-OFDMA....12
B. CHANNEL MODEL....13
a. Large-Scale Propagation Loss....15
b. Small-Scale Propagation Loss....15
c. Rayleigh Fading Model....19
C. MAXIMAL RATIO COMBINING....19
D. SUMMARY....21

III. PERFORMANCE ANALYSIS OF PARTIAL BAND JAMMING AGAINST 802.16A....23
A. OVERVIEW....23
B. SIGNAL PERFORMANCE IN AWGN WITH BROADBAND AND NARROWBAND INTERFERENCE WITHOUT MRC....24
1. Unintentional Interference....25
a. Constant Data Rate and Modulation Scheme Plots....26
b. Constant Level of Partial or Full Band Interference Plots....30
2. Intentional Interference....34
C. SIGNAL PERFORMANCE IN AWGN WITH BROADBAND AND NARROWBAND INTERFERENCE WITH MRC....38
1. 54 Mb/s, Constant MRC with Unintentional Interference....40
2. 54 Mb/s, Constant PBI with Unintentional Interference....45
3. 12 Mb/s, Constant MRC with Unintentional Interference....50
4. 12 Mb/s, Constant PBI with Unintentional Interference....55

IV. SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK....61
A. SUMMARY....61
B. FUTURE WORK....61

LIST OF REFERENCES....63

INITIAL DISTRIBUTION LIST....65

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

Figure 1 IEEE 802.16 Protocol Structure showing SAP's (From Ref. [1].) 5
Figure 2 Example of TDD (From Ref.[1]). 6
Figure 3 802.16a MAC Features (From Ref. []). 7
Figure 4 Fundamental Burst Framing Elements (Ref. [11]). 9
Figure 5 Pilot Word Patterning within a Burst (Ref. [1].) 9
Figure 6 OFDM Frequency Description (Ref. [1]). 10
Figure 7 OFDMA Frequency Domain and Subchannels (From Ref. [1]) 12
Figure 8 Multipath Fading Environment (From Ref. []). 14
Figure 9 12 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 26
Figure 10 12 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 26
Figure 11 36 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 27
Figure 12 36 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 27
Figure 13 54 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 28
Figure 14 54 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 28
Figure 15 PBI=25, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate. 30
Figure 16 PBI=25, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate. 30
Figure 17 PBI = 50, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate. 31
Figure 18 PBI = 50, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate. 31
Figure 19 PBI = 100, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate. 32
Figure 20 PBI = 100, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate. 32

Figure 21 PBI = 200, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate.....33
Figure 22 PBI = 200, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate.....33
Figure 23 12 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed. 35
Figure 24 12 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed. 35
Figure 25 36 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed. 36
Figure 26 36 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed. 36
Figure 27 54 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed. 37
Figure 28 54 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed. 37
Figure 29 54 Mb/s, MRC =1, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 40
Figure 30 54 Mb/s, MRC =1, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 40
Figure 31 54 Mb/s, MRC =48, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 41
Figure 32 54 Mb/s, MRC =48, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 41
Figure 33 54 Mb/s, MRC =96, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 42
Figure 34 54 Mb/s, MRC =96, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 42
Figure 35 54 Mb/s, MRC =192, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 43

Figure 36 54 Mb/s, MRC =192, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 43
Figure 37 54 Mb/s, PBI = 25, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 45
Figure 38 54 Mb/s, PBI = 25, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 45
Figure 39 54 Mb/s, PBI = 50, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 46
Figure 40 54 Mb/s, PBI = 50, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 46
Figure 41 54 Mb/s, PBI = 100, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 47
Figure 42 54 Mb/s, PBI = 100, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 47
Figure 43 54 Mb/s, PBI = 200, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 48
Figure 44 54 Mb/s, PBI = 200, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 48
Figure 45 12 Mb/s, MRC =1, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers....50
Figure 46 12 Mb/s, MRC =1, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 50
Figure 47 12 Mb/s, MRC =48, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 51

Figure 48 12 Mb/s, MRC =48, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 51
Figure 49 12 Mb/s, MRC =96, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 52
Figure 50 12 Mb/s, MRC =96, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 52
Figure 51 12 Mb/s, MRC =192, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 53
Figure 52 12 Mb/s, MRC =192, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers. 53
Figure 53 12 Mb/s, PBI=25, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.....55
Figure 54 12 Mb/s, PBI=25, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 55
Figure 55 12 Mb/s, PBI=50, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.....56
Figure 56 12 Mb/s, PBI=50, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 56
Figure 57 12 Mb/s, PBI=100, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 57
Figure 58 12 Mb/s, PBI=100, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 57
Figure 59 12 Mb/s, PBI=200, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 58
Figure 60 12 Mb/s, PBI=200, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition. 58

LIST OF TABLES

Table 1 Summary of Various 802.16 Technology Specifications (From Ref. []). 4
Table 2 802.16A PHY Layer Features (From Ref.[10]) 8
Table 3 OFDM Symbol Parameters (From Ref. [1]). 11
Table 4 OFDMA DL Carrier Allocations (From Ref. [1]). 13
Table 5 Types of Small Scale Fading (After Ref. [11]) 18

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AAS	Adaptive Antennas System
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
BWA	Broadband Wireless Access
CIR	Channel Impulse Response
CP	Cyclic Prefix
CTC	Convolutional Turbo Codes
DAC	Digital to Analog Converter
DEMUX	Demultiplexer
DFT	Discrete Fourier Transform
DL	Downlink
DSL	Digital Subscriber Line
ETSI	European Telecommunications Standard Institute
FCH	Frame Control Header
FDD	Frequency Division Duplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
FSK	Frequency shift keying
GUI	Graphical User Interface
HDD	Hard Decision Decoding
ICI	Inter-carrier Interference
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
ISI	Inter-symbol Interference
LAN	Local Area Network
LO	Local Oscillator

MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML	Maximum Likelihood
MP-MP	Multipoint-to-Multipoint
MRC	Maximal Ratio Combining
MUX	Multiplexer
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDF	Probability Density Function
PDS	Power Delay Spectrum
PER	Packet Error Rate
PMP	Point to Multipoint
PHY	Physical Layer
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RMS	Root Mean Square
RS	Reed-Solomon Code
SAP	Service Access Point
SCa	802.16a-Single Carrier
SDD	Soft Decision Decoding
SIMO	Single Input Multiple Output
SNR	Signal to Noise Ratio
SS	Subscriber Substation
TDD	Time Division Duplexing
UL	Uplink
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network

ACKNOWLEDGMENTS

I would like to thank my girlfriend Kelly for standing by me and being extremely supportive and understanding while I completed this thesis. Additionally, I would like to thank Professor Ha for his guidance and his willingness to help. Finally, the above and beyond assistance and guidance of LT Mike Herlands, USN, was invaluable in finishing this thesis.

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

The demand for reliable, high-speed wireless communications will only continue to grow in the upcoming years. This demand has spread to places where high-speed Internet was previously unfeasible due to the infrastructure limits of wire line systems such as cable and digital subscriber line (DSL) systems. There are many wireless communication standards already developed and in use today, such as 802.11g or "Wi-Fi," and numerous proprietary systems but they have certain limitations. The IEEE 802.16a standard is a very promising standard with immense interest in the commercial and military sectors. The standard provides for broadband wireless access (BWA) in the 2-11 GHz band of spectrum and can accommodate Non Line of Sight (NLOS) communications [1]. In order to provide high data rates, the standard utilizes three modes of modulation. The three modes are: single carrier (SCa), orthogonal frequency division multiplexing (OFDM), and orthogonal frequency division multiple access (OFDMA) [1]. This thesis includes a performance analysis of the standard against different types of jamming and white noise using a simulation in MATLAB®. Potential military situations such as those with enemies intentionally or unintentionally interfering with wireless communications were simulated to explore the extent of the usefulness of this standard for military communications.

OFDM provides for the transmission of broadband signals in a manner such that the signal experiences flat fading while transmitting at a high data rate. OFDM uses overlapping multiple orthogonal subcarriers which is spectrally efficient. OFDM is less susceptible to frequency selective fading because of the narrow bandwidths of the individual subcarriers.

In the 802.16a standard, synchronization is of the utmost importance. If any frequency offset occurs during transmission, intercarrier interference (ICI) develops at the receiver. Alternatively, timing problems at the beginning of the OFDM symbol can cause ISI. Channel estimation is a critical portion of the 802.16a standard and is performed by using a preamble. Coherent detection, equalization and Maximal Ratio

Combining (MRC) would not be feasible without channel estimation. Frequency synchronization is also critical to the spectrally efficient OFDM with its overlapping subcarriers.

The objective of this thesis was to extend the analysis of the IEEE 802.16a done by MAJ Smith, USMC [2] examining partial band jamming against 802.16a. The 802.16a code was modified with repetition coding to repeat the data 48, 96 or 192 times to examine the effects of reducing the data to enhance performance and robustness to interference. The model was tested in the presence of: AWGN only, AWGN plus a broadband unintentional interference signal, AWGN plus narrowband unintentional interference signals, AWGN plus a broadband intentional interference signal and AWGN plus narrowband intentional interference signals. Partial band jamming was added to 1/8, ¼ and ½ of the total non null subcarriers. The effects of unintentional interference vs. intentional interference were explored to determine if the total amount of power or the placement of the interference signal was the most significant factor. The repeated data was combined at the receiver using MRC. The overarching objective of this project was to provide useful information to the U.S. Military about wireless communications in harsh environments.

The results of the research followed the expectations. It was expected that as the user reduced the data rate through the use of the repetition code, the performance would improve. The data rates of 54 Mb/s and 12 Mb/s were chosen for rigorous testing as 54 Mb/s offered the greatest data rate with the poorest reliability while 12 Mb/s is the lowest supported data rate with the greatest reliability. With ½ of the channels experiencing jamming, the effects of repetition and MRC were tested on 54 Mb/s and 12 Mb/s. There was an improvement of nearly 18 dB by repeating the data 48 times with a 54 Mb/s data rate. The same amount of repetition yielded an improvement of only 4 dB for 12 Mb/s. Additionally, as the repetition increased from 48 to 192, the amount of improvement reduced while the increased repetition had a larger effect on the total data rate. Repeating the data 48 times yielded the largest performance gains for the smallest reduction in data rate. It was also found that the impact of repetition coding increased with the data rate. Finally, through testing with intentional interference, it was determined that the amount

of interference power is a more significant factor than the placement of interference power. The performance of the system against the different types of jamming was enhanced significantly through the use of MRC. The standard proved itself to be a robust and potentially viable option for military wireless communications in harsh environments.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. BACKGROUND

The IEEE 802.16 standard provides for Broadband Wireless Access (BWA) that offers a broadband connection and a low cost solution to extend the Internet to the end user in the 11-66 GHz range. Approved two years after 802.16, the IEEE 802.16a standard provides for BWA for the global deployment of broadband Wireless Metropolitan Area Networks (WMANs) [1]. 802.16a operates in the 2-11 GHz range and provides for Non Line of Sight (NLOS) communications. The commercial and military demand for new and improved wireless technologies in new innovative uses is strong. The military is interested in this wireless technology as it could enhance the capabilities of the systems in use today and provide a low cost option in comparison to similar military radio systems.

B. OBJECTIVE

The objective of this thesis was to extend the analysis of the IEEE 802.16a done by MAJ Smith, USMC [2] by examining partial band jamming against 802.16a. The 802.16a was modified with repetition coding and tested in the presence of: AWGN only, AWGN plus a broadband unintentional interference signal, AWGN plus narrowband unintentional interference signals, AWGN plus a broadband intentional interference signal and AWGN plus narrowband intentional interference signals. This thesis tested the interference against a receiver utilizing Maximal Ratio Combining. The overarching objective of this project was to provide useful information to the U.S. Military about wireless communications in harsh environments.

C. RELATED WORK

This study extends the work done by LT Herlands, which was an examination of the effects partial band jamming against an IEEE WLAN standard, 802.11g with diversity and MRC [3]. It was found repeating the data offered the user a option to have

greater performance at the cost of data throughput [3]. He developed the partial band jamming algorithm which randomly assigned interference to the specified number of subcarriers. The testing phase of this thesis closely followed his procedure.

This thesis took the developed partial band jamming algorithm and the established testing procedure and applied them to the 802.16a code modified by MAJ Smith in his thesis [2]. MAJ Smith modified the code by repeating the data 48, 96 or 192 times and recombining the data with MRC [2]. .

D. THESIS ORGANIZATION

This thesis provides an overview of the 802.16a standard's architecture, MAC and PHY layers as well as channel model issues. MRC and OFDM are also discussed.

The thesis is organized into the following chapters:

Chapter II provides an overview the 802.16a standard's architecture, MAC layer and physical layer. Additionally, the chapter discusses the channel model used, the concept of Maximal Ratio Combining and propagation loss.

Chapter III contains the simulations of 802.16a against partial band jamming. This chapter includes a presentation of the results of the simulations with accompanying discussions of all the findings.

Chapter IV provides the conclusions and presents recommendations for future work.

This chapter gave an introduction to the material to be covered in the thesis. The chapter offered a broad overview of the standard and its relevance for academic study. The next chapter will provide an overview of broadband wireless networking as well as the MAC and PHY layers of the 802.16a standard. Additionally, the chapter discusses the concepts of OFDM, channel models and the concept of Maximal Ratio Combining.

II. BACKGROUND

The IEEE 802.16's Task Group a (TGa) developed the IEEE standard 802.16a to provide specifications for the 2-11 GHz range. The standards to define the medium access control and physical layer specifications were designed by this group and are explored in this thesis.

This chapter discusses the 802.16a standard beginning with a general overview of the system architecture. The chapter also provides information about the MAC and PHY layers of the standard, specifically focusing on the Wireless MAN-OFDM mode of the PHY layer.

Additionally, this chapter discusses large scale and small scale fading with a focus on multipath. Multipath fading is the biggest impairment to wireless communications in this type of network.

A. IEEE 802.16A OVERVIEW

Approved in 2001, the IEEE 802.16 standard provides for BWA in the 10-66 GHz range [4]. With such high frequencies, attenuation is a large problem for non line of sight (NLOS) communications [4]. In 2003, the IEEE published 802.16a, which is an amendment to 802.16 allowing for communications in the 2-11 GHz range [4]. In this frequency range, the wavelength is larger than in 10-66 GHz and so the standard can handle NLOS communications. In the 2-11 GHz range are unlicensed signals so to meet the challenges associated with unlicensed bands and NLOS, advanced power management techniques are critical to 802.16a. These techniques reduce interference from the channel and from other users while abiding by the power restrictions in the unlicensed bands. Since 2001, there have been a variety of different standards within the 802.16 family either written or in development to meet different goals. These different standards are listed below in Table 1. [5]

Specifications	Year of Ratification	Description
802.16 [1]	2001	MAC and PHY definition for fixed broadband wireless access in the 10-66 GHz bands
802.16a [2]	2003	Amendment contains new PHY definitions for 2-11GHz bands.
802.16c [3]	2002	System profiles for 10-66 GHz operations
802.16d [4]	2004	Contains 802.16, 802.16a, and various MAC enhancements. Considered the base for fixed broadband wireless specification
802.16e	2005	Amendment to 802.16d specification. Explicit support for mobility.
802.16f	2005	802.16 Management Information Base (MIB)
802.16g	In Progress	Network Management
802.16h	In Progress	Coexistence in license exempt frequency bands
802.20	In Progress	Mobile broadband wireless access standards group. Focus on mobility supporting train-like speeds.
WiBRO		Korean wireless broadband standard, to be incorporated into upcoming 802.16e standard

Table 1 Summary of Various 802.16 Technology Specifications (From Ref. [6]).

1. System Architecture Overview

Broadband Wireless Access (BWA) system architecture is similar to cellular networks in that there are fixed Base Stations (BSs) and Subscriber Stations (SSs). BWA systems require fixed infrastructure sites like cellular networks. The BSs provide the link to the wired backbone of the network and to the wireless SSs. A coverage area is made up of one BS and one or multiple SSs which can be grouped together. The BSs remain interconnected. BWA also heavily relies on frequency reuse like cellular networks. [7]

BSs provide point to multi point (PMP) to communicate with multiple SSs. Additionally, there are mesh networks, or multi-point to multi-point (MP-MP). With MP-MP technology, the SSs can communicate with other SSs without going through the BS. BSs can use sectorized antennas while SSs often use highly directional antennas pointed for optimal data rates. BSs even allow for the use of adaptive antenna systems (AAS) to dynamically steer antenna beams as communication and channel requirements change. This system allows 802.16 to achieve higher data rates than 802.11 which did not specify directional antennas. The downlink (DL) refers to the BS to SS communications while the uplink (UL) refers to the SS to BS communications. [7]

2. The 802.16 MAC Layer

The Medium Access Control (MAC) layer is divided into three sublayers which are the convergence sublayer (CS), the common part sublayer (CPS) and the security sublayer [1]. There are assumed to be two types of traffic on the network: a) asynchronous transfer mode (ATM) cells and b) Internet Protocol (IP) packets [8]. The relations between the MAC sublayers and PHY layer as well as the Service Access Points (SAP) are shown below in Figure 1.

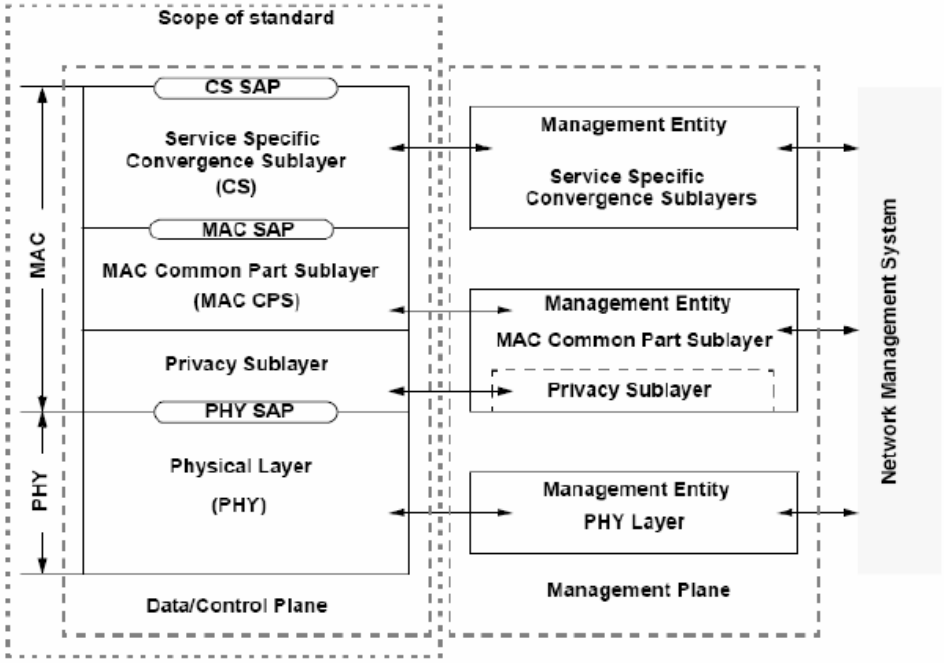

Figure 1 IEEE 802.16 Protocol Structure showing SAP's (From Ref. [1].)

Channelization, which divides the wideband signal into smaller narrowband signals [9], is accomplished through time division multiplexing (TDM). The UL and DL are separated by duplexing. Specifically, time-division duplexing (TDD) and frequency-division duplexing (FDD) separate the UL and DL. In TDD, each frame is composed of an UL sub-frame and a DL sub-frame. In FDD however, the UL and DL sub-frames are transmitted through different frequency channels. TDD is illustrated in the figure below, Figure 2. [1]

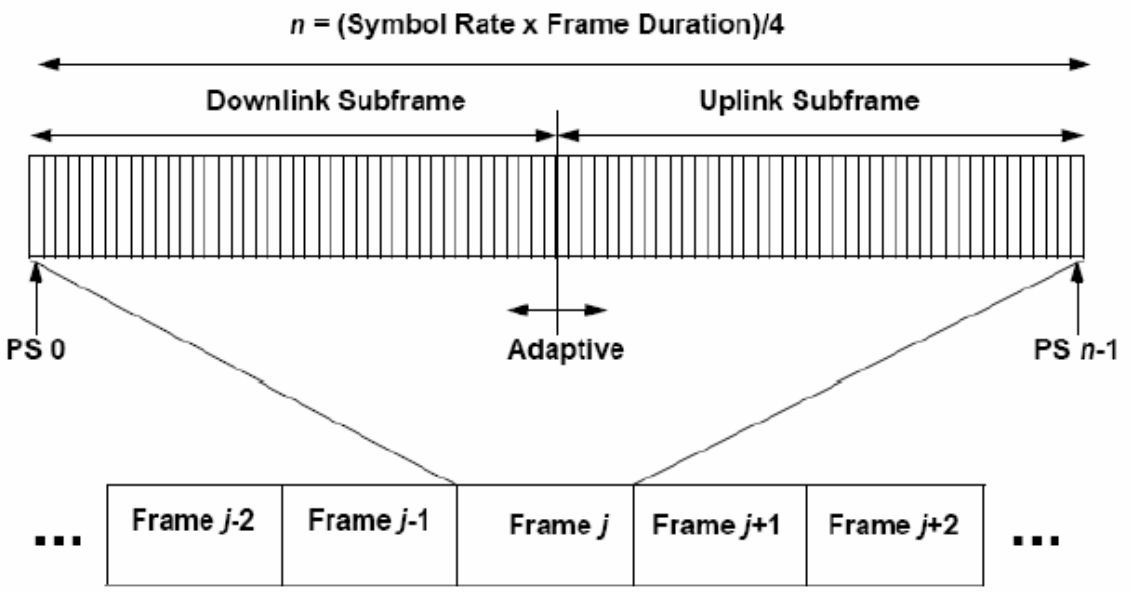

Figure 2 Example of TDD (From Ref.[1]).

The MAC layer is connection oriented. The MAC layer controls quality-of-service, security issues and the access schemes to support multiple users. Additionally, the MAC controls the procedures to define burst start times. Features of the MAC are listed below in Figure 3. [1]

Feature	Benefit
TDM/TDMA Scheduled Uplink/Downlink frames.	• Efficient bandwidth usage
Scalable from 1 to hundreds of subscribers	• Allows cost effective deployments by supporting enough subs to deliver a robust business case
Connection-oriented	• Per Connection QoS • Faster packet routing and forwarding
QoS supportContinuous GrantReal Time Variable Bit RateNon Real Time Variable Bit RateBest Effort	• Low latency for delay sensitive services (TDM Voice, VoIP) • Optimal transport for VBR traffic(e.g., video) Data prioritization
Automatic Retransmission request (ARQ)	• Improves end-to-end performance by hiding RF layer induced errors from upper layer protocols
Support for adaptive modulation	• Enables highest data rates allowed by channel conditions, improving system capacity
Security and encryption (Triple DES)	• Protects user privacy
Automatic Power control	• Enables cellular deployments by minimizing self interference

Figure 3 802.16a MAC Features (From Ref. [10]).

3. The 802.16 PHY Layer

The purpose of the 802.16a PHY layer is to transmit messages from the MAC layer. The messages are transmitted using QPSK, 16 QAM, or 64 QAM modulations and the PHY layer changes the modulation adaptively. The PHY layer achieves this task through the use of two sublayers which are the transmission convergence sublayer and the physical medium dependent sublayer. The MAC layer accesses the PHY layer through Service Access Points (SAPs) to transmit its messages. The PHY layer sends the messages wirelessly in the 2-11 GHz band. . A few of the more beneficial features of the PHY are listed in Table 2. The PHY layer uses these three methods to transmit and receive data: [1]

- Single-Carrier (SCa)
- OFDM
- OFDMA

Feature	Benefit
256 point FFT OFDM waveform	• Built in support for addressing multipath in outdoor LOS and NLOS environments
Adaptive Modulation and variable error correction encoding per RF burst	• Ensures a robust RF link while maximizing the number of bits/ second for each subscriber unit.
TDD and FDD duplexing support	• Address varying worldwide regulations where one or both may be allowed
Flexible Channel sizes (e.g. 3.5MHz, 5MHz, 10MHz, etc)	• Provides the flexibility necessary to operate in many different frequency bands with varying channel requirements around the world.
Designed to support smart antenna systems	• Smart antennas are fast becoming more affordable, and as these costs come down their ability to suppress interference and increase system gain will become important to BWA deployments.

Table 2 802.16A PHY Layer Features (From Ref.[10]).

a. Wireless Man-SCa

The Wireless Man-SCa PHY is based on single carrier technology and sends all its data on one very high data rate channel. Similar to the other modes, it is designed for NLOS operations in the 2-11 GHz frequency bands. This is the only mode not to use OFDM. [1]

This mode uses the Framed Burst format for both the DL and UL data. The DL supports the Time Division Multiplex (TDM) bursts while the UL supports TDMA (Time Division Multiple Access) bursts. The difference between the two is that TDM bursts are separated by preambles and gaps in transmission while TDMA bursts are not separated. Furthermore, TDMA uses a central scheduler to allocate the UL bandwidth while TDM does not. An overall DL or UL subframe consists of many burst frames. The preamble contains a ramp up period followed by the preamble body. The preamble consists of Unique Words which aid in channel estimation. The general burst frame format is shown below in Figure 4. [1]

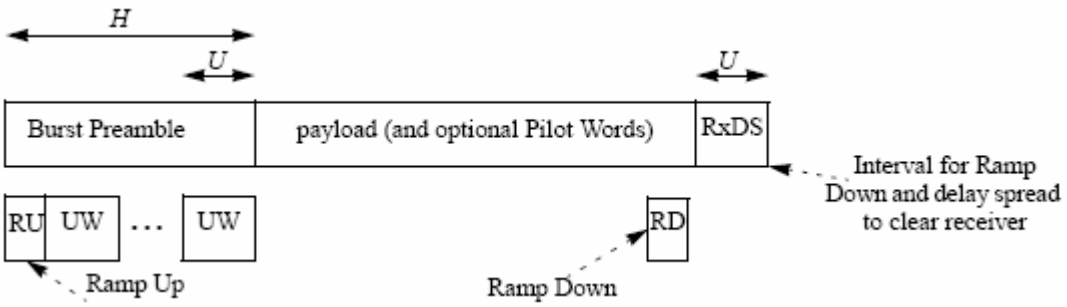

Figure 4 Fundamental Burst Framing Elements (Ref. [11]).

After the burst preamble comes the burst payload which carries the data and may contain periodically inserted Pilot Words. A payload word, which includes the payload data and the optional Pilot Word, is made up of *F* symbols. Out of the *F* symbols, *P* of them are for the optional Pilot Word which is an integer multiple of unique words. *F* is constant for the burst when Pilot Words are being transmitted. Transmission of the pilot symbols stops when there are *F-P* or fewer symbols left. The payload architecture is shown below in Figure 5.[1]

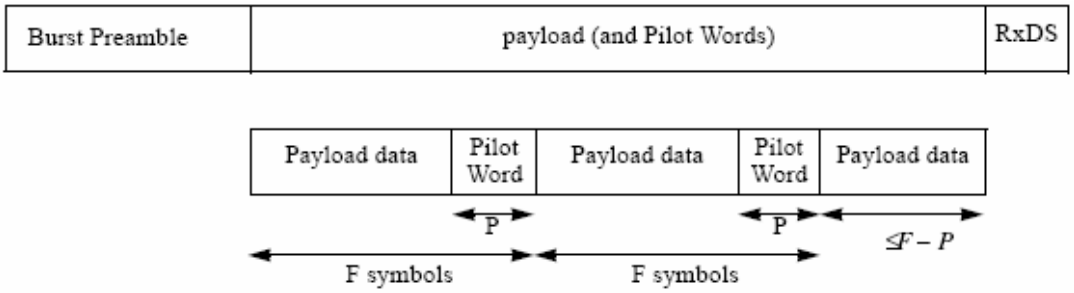

Figure 5 Pilot Word Patterning within a Burst (Ref. [1].)

b. Wireless Man – OFDM

The widespread use of orthogonal frequency division multiplexing (OFDM) in wireless communications was not a reasonable option until recently. The development of improved nanotechnology chips that can perform complex mathematical operations allows for OFDM to be done without complex algorithms at the receiver

which was the primary obstacle to OFDM. The chip uses the Inverse Fast Fourier Transform (IFFT) to put the signal into the time domain from the frequency domain. As OFDM transmits the bits in parallel, each bit can be longer for the same bit rate which greatly mitigates the fading effects of the channel. Additionally, parallel transmission increases the data rate. Also, there is a cyclic prefix appended to the beginning of each symbol to act as a buffer against ISI by reducing the multipath and delay spread effects. Below is a diagram of the 802.16a WirelessMAN-OFDM Frequency Description in Figure 6.[1]

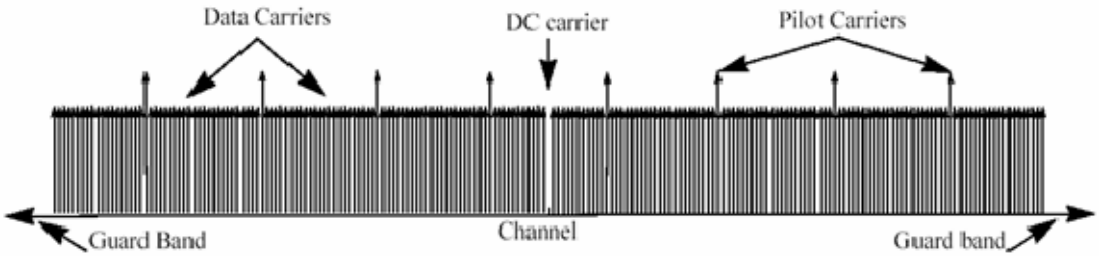

Figure 6 OFDM Frequency Description (Ref. [1]).

OFDM is the modulation of choice due to its ability to mitigate most common distortions from multipath. Most communications systems use expensive adaptive filters while OFDM instead employs guard intervals between symbols to counter time domain smearing. As each data symbol is modulated on a different subcarrier, the transmitted signal becomes [1]

$$s(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \sum_{\substack{k=-\frac{N_{used}}{2} \\ k\neq 0}}^{\frac{N_{used}}{2}} c_k \cdot e^{j2\pi k\Delta f (t-T_g)} \right\}, \qquad (1)$$

where c_k is the complex baseband modulation symbol, Δf is the sampling frequency divided by the number of points in the Fast Fourier Transform (FFT) $f_{\text{sample}}/\text{N}_{\text{FFT}}$, and T_g is the length of the cyclic prefix. Table 3 provides many Wireless MAN OFDM symbol parameters. Of the 256 total subcarriers available, 200 are used subcarriers, while the

remaining 56 are null subcarriers, meaning they have no transmit power. Of the 200 used, 8 are pilot carriers while 192 are data carriers. The remaining 56 null carriers are divided with 55 as guard bands and one as the DC carrier. The guard bands allow separation against neighboring channels. [1]

Parameter	Value
N_{FFT}	256
N_{used}	200
F_s / BW	licensed channel bandwidths which are multiples of 1.75 MHz and license-exempt: 8/7 any other bandwidth: 7/6
(T_g / T_b)	1/4, 1/8, 1/16, 1/32
Number of lower frequency guard carriers	28
Number of higher frequency guard carriers	27
Frequency offset indices of guard carriers	−128,−127...,−101 +101,+102,...,127
Frequency offset indices of BasicFixedLocationPilots	−84,−60,−36,−12,12,36,60,84
Subchannel number: Allocated frequency offset indices of carriers	1:{−88,...,−76},{−50,...,−39},{1,...,13},{64,...,75} 2:{−63,...,−51},{−25,...−14},{26,...,38},{89,...,100} 3:{−100,...,−89},{−38,...,−26},{14,...,25},{51,...,63} 4:{−75,...,−64},{−13,...,−1},{39,...,50},{76,...,88}

Table 3 OFDM Symbol Parameters (From Ref. [1]).

Another benefit of OFDM is that it uses eight dedicated pilot carriers, which allows for improved synchronization and phase tracking. Each of the eight pilot carriers transmits the same pilot symbol which is derived from a pseudorandom sequence. In the SCa mode, Pilot Words can only be sent periodically. For all of these

reasons, OFDM is considered the best choice when optimizing cost and performance for Wireless MANs when compared to SCa. [1]

c. Wireless MAN-OFDMA

Wireless MAN-orthogonal frequency division multiple access (OFDMA) segments the various subcarriers into subchannels for both the UL and DL to support multiple users. The data is divided on the subchannels so that OFDMA symbols are mapped in the time domain via TDMA but also must be mapped to the specific subchannel on which each symbol will be transmitted, thereby resulting in a two-dimensional "data region." Several segmented subchannels are shown below in Figure 7.[1]

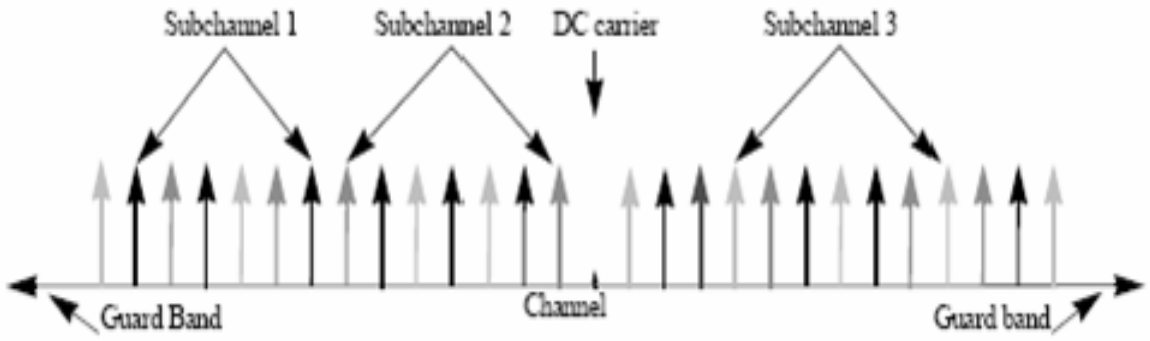

Figure 7 OFDMA Frequency Domain and Subchannels (From Ref. [1]).

The BS can selectively transmit subchannels whereas the SS is assigned one or more subchannels. Table 4 lists notable features of OFDMA. Another element of OFDMA is that in addition to fixed location pilots, there are variable location pilot carriers. The variable pilot location changes every symbol and repeats every four. [1]

Parameter	Value
Number of dc carriers	1
Number of guard carriers, left	173
Number of guard carriers, right	172
N_{used}, Number of used carriers	1702
Total number of carriers	2048
$N_{varLocPilots}$	142
Number of fixed-location pilots	32
Number of variable-location pilots which coincide with fixed-location pilots	8
Total number of pilots[a]	166
Number of data carriers	1536
$N_{subchannels}$	32
$N_{subcarriers}$	48
Number of data carriers per subchannel	48
BasicFixedLocationPilots	{0,39, 261, 330, 342, 351, 522, 636, 645, 651, 708, 726, 756, 792, 849, 855, 918, 1017, 1143, 1155, 1158, 1185, 1206, 1260, 1407, 1419,1428, 1461, 1530,1545, 1572, 1701}
$\{PermutationBase_0\}$	{3, 18, 2, 8, 16, 10, 11, 15, 26, 22, 6, 9, 27, 20, 25, 1, 29, 7, 21, 5, 28, 31, 23, 17, 4, 24, 0, 13, 12, 19, 14, 30}

[a]Variable Location Pilots which coincide with Fixed-location Pilots are counted only once in this value.

Table 4 OFDMA DL Carrier Allocations (From Ref. [1]).

B. CHANNEL MODEL

Determining the channel model is one of the most difficult aspects of engineering wireless communications but is also one of the most important. The transmission path between the transmitter and receiver can vary between a complex path with buildings, foliage and obstacles to a relatively simple line of sight path. Radio channels are not fixed like wired channels and the constant changing is a major consideration. Channel

modeling is typically done in a statistical fashion. In this thesis, a Rayleigh fading model is used as the channel model for NLOS communications. [11]

1. Multipath Fading

There are many elements that go into the study of the propagation of electromagnetic waves. Three of the most important factors in the losses the waves experience are reflection, diffraction and scattering. In any environment, but particularly in a dense urban environment, it may not be possible to have direct line of sight communications. An example of a multipath fading environment with reflectors is shown below in Figure 8. [11]

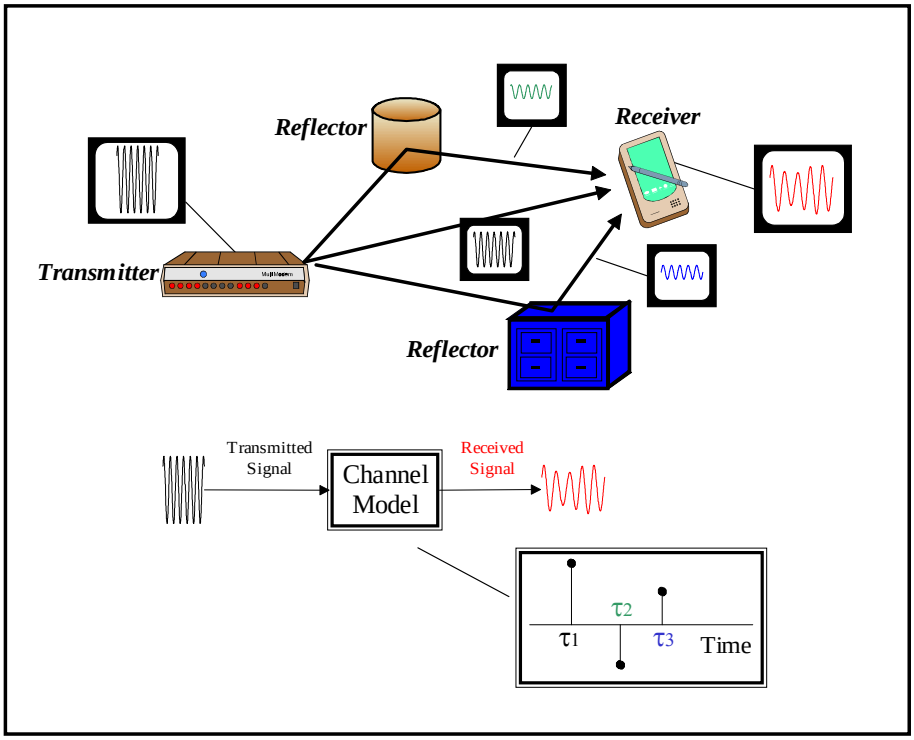

Figure 8 Multipath Fading Environment (From Ref. [12]).

High rise buildings, dense urban environments and foliage can cause significant losses from reflection and scattering. In a real world setting, the wave will be reflected off of multiple surfaces in its trip from the transmitter to the receiver. As seen in Figure 8 reflecting objects and other scatterers create a multipath channel. There are multiple

overlapping versions of the transmitted signal at the receiver antenna which the receiver must decipher. This is known as multipath fading. [11]

The type of fading determines the mathematical model used in simulating the transmissions. The factors in deciding which type of fading is most prevalent are RMS delay spread, coherence bandwidth, and Doppler spread or coherence time. The different factors are used to characterize if the radio channel experiences flat or frequency selective fading and whether the channel undergoes fast or slow fading. [11]

a. Large-Scale Propagation Loss

Large scale propagation models are those that focus on determining the mean signal strength for a large (100-10000m) transmitter receiver separation distance [11]. In the large scale propagation modeling, the three most important factors are distance, antenna height and frequency [11]. The 802.16a standard is designed to work in metropolitan areas and so the model must be chosen accordingly [1].

b. Small-Scale Propagation Loss

There are a number of physical factors that influence the severity and type of small scale fading a radio propagation channel experiences. They are multipath propagation, the speed of the mobile, speed of the surrounding objects and the transmission bandwidth. The speed of the mobile is unimportant because in the case of WLANs the end user is either not moving at all or moving very little. The speed of the surrounding objects is only important when their speed is greater than the speed of the mobile which is the case in a WLAN. [11]

Small scale fading can not be described by equations such as in the Okumura-Hata model because the channel is dynamic. It is a stochastic process and can be defined only in terms of probabilities and statistical averages. [13]

In order to compare multipath channels and fading effects, there must be parameters to measure the channels. Some of the main parameters used are mean excess delay, RMS delay spread and excess delay spread. Mean excess delay ($\bar{\tau}$) and RMS

delay spread (σ_τ) are the most commonly used parameters. [11] The mean excess delay is the first moment of the power delay profile and is defined as

$$\bar{\tau} = \frac{\sum_k a_k{}^2 \tau_k}{\sum_k a_k{}^2}, \tag{2}$$

where a_k is the received signal amplitude at the given excess delay τ_κ where the transmitted signal is $P(\tau_k) = a_k{}^2$ [11]. The RMS delay spread, the standard deviation of the power delay spread, is [11]

$$\sigma_\tau = \sqrt{\frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} - (\bar{\tau})^2} \tag{3}$$

.

Given that a channel is wide sense stationary or time-invariant over small-scale time, then the channel impulse response is described as

$$h_b(\tau) = \sum_{i=0}^{N-1} a_i \exp(j\theta_i)\delta(\tau - \tau_i), \tag{4}$$

where a_i and θ_i are the amplitude and phase of the from the *i*-th path and δ is Dirac delta function [11]. The power delay profile is given by

$$P(\tau) = \overline{k\left|h_b(t;\tau)\right|^2} \tag{5}$$

where $h_b(t;\tau)$ is the result of $h_b(\tau)$ after being used with a probing pulse $p(t) \approx \delta(t-\tau)$ to sound the channel. .Specifically, the power delay profile is the received power expressed as a function of the excess delay when the channel is excited by a probing pulse $p(t) \approx \delta(t-\tau)$. [11]

In the coherence bandwidth, the signal will usually experience roughly the same attenuation and linear phase shift which makes detection easier [11]. The channel

is considered “flat” within the coherence bandwidth and it is the range in which two different frequencies will have high correlation of attenuation [11]. There are two general equations for coherence bandwidth, each defined for a different value of the correlation. For a correlation of 0.9, the equation is [11]

$$B_c \approx \frac{1}{50\sigma_\tau} \tag{6}$$

while for 0.5, the equation is

$$B_c \approx \frac{1}{5\sigma_\tau} \tag{7}$$

Doppler spread and coherence time describe the time varying property of the channel. Frequency dispersion is caused by the motion of objects in the channel or by the relative motion of the base station and the end user which causes the frequency of the signal to change. Coherence time is the time domain equivalent of the Doppler spread and is inversely proportional to the Doppler spread. Coherence time is the time duration during which the channel impulse response is roughly time invariant. The geometric mean is the metric used to calculate coherence time and is given as [11],

$$T_C = \sqrt{\frac{9}{16\pi f_m^2}} \approx \frac{0.423}{f_m}, \tag{8}$$

where f_m is the maximum Doppler shift. [11]

Small-Scale Fading (based on multipath delay spread)	
Frequency Non-selective (Flat) Fading	***Frequency Selective Fading***
1. BW of Signal < Coherence BW of Channel 2. Delay Spread < Symbol Period	1. BW of Signal > Coherence BW of Channel 2. Delay Spread > Symbol Period

Small-Scale Fading (based on Doppler spread)	
Fast Fading	***Slow Fading***
1. High Doppler Spread 2. Coherence Time < Symbol Period 3. Channel Variations Faster than Baseband Signal Variations	1. Low Doppler Spread 2. Coherence Time > Symbol Period 3. Channel Variations Slower than Baseband Signal Variations

Table 5 Types of Small Scale Fading (After Ref. [11]).

By looking at Table 5 it can be seen that the slow fading model is the most accurate for 802.16a. The Doppler spread is negligible, if not zero, as the receiver and transmitter are specified to be fixed in the standard [1]. This is shown below. The maximum relative velocity in the channel is assumed to be a car traveling at a speed of 100 km/hr, or 62.2 mph, and a likely center frequency supported by the standard is 5 GHz. Under these assumptions the Doppler shift would be

$$f_m = vf_c / c$$
$$f_m = 27.8m/s * 5x10\,\text{^}\,9Hz / 3x10\,\text{^}\,8m/s$$
$$f_m = 462.95Hz$$

Also, there is a long coherence time which accommodates parallel transmission and the subsequent longer symbol durations. Using equation 8, an approximate coherence time can be determined.

$$T_C = \sqrt{\frac{9}{16\pi f_m^2}} \approx \frac{0.423}{f_m}$$
$$T_C = .423/462.95Hz$$
$$T_C = 9.13x10^{-4}s$$

Each symbol can be longer for the same bit rate which reduces the fading effects of the channel [5]. Using a center frequency of 11 GHz, a worst case coherence time can be found using the same equations. This value is $T_C = 4.15x10^{-4} s$.

Coherence bandwidth is one of OFDM's primary advantages in terms of fading. RMS delay spreads in outdoor environments vary from 100 ns to 5.3 μs [14]. The corresponding coherence bandwidths are between 188.7 kHz and 10 MHz. Under a worst-case scenario, a coherence bandwidth of 188 kHz would result in a highly frequency selective fading channel for a single-carrier transmission of 7 MHz. In 802.16a, 7 MHz is a valid single-carrier bandwidth. The benefit of OFDM is that an OFDM symbol with 200 subcarriers taking up 7 MHz of bandwidth would have individual subcarrier bandwidths of only 35 kHz allowing each individual subcarrier's signal to operate in a flat fading channel [1]. Hence, in the frequency domain, each subcarrier's symbol is uniformly attenuated. [5]

c. Rayleigh Fading Model

The Rayleigh fading model is a statistical model used to describe a flat fading signal in a NLOS channel with significant multipath. The model is most appropriate in dense urban environments such as major metropolitan areas where the BS is shorter than its surroundings. The received signal amplitude is modeled to have a Rayleigh distribution. [13] The probability density function of the Rayleigh distribution is [11];

$$p(z) = \frac{z}{\sigma^2}\exp(-\frac{z^2}{2\sigma^2}) \quad z \geq 0, \tag{9}$$

where $2\sigma^2 = E\{z^2\}$.

C. MAXIMAL RATIO COMBINING

Maximal ratio combining is a method of diversity combining in which signals from each channel are added together before being normalized to the root mean square of

the signal amplitude. When used with multiple antennas, this technique can maximize the instantaneous SNR. The coefficients that yield the maximum SNR are calculated using an optimization theory. In this thesis, instead of testing multiple antennas and combining their inputs, the same data was repeated on multiple subcarriers and MRC was used to combine the subcarriers. [15] The complex envelope of the received signal for a single symbol on carrier l can be written as

$$r_l = h_l s + v_l \tag{10}$$

,

where h_l is the complex channel attenuation per subcarrier, *s* is the transmitted signal, *l* is a specific data subcarrier and v_l are the complex Gaussian noise samples [15]. The complex channel attenuation includes the effects of attenuation and phase shift by flat, slow fading. The technique calls for the use of linear combinations of the signal:[12]

$$y = \sum_{l=1}^{L} w_l^* r_l = \sum_{l=1}^{L} w_l^* h_l s + \sum_{l=1}^{L} w_l^* v_l \tag{11}$$

where L is the diversity which is the number of data subcarriers carrying the identical signal and also equals the number of data subcarriers to be combined in the demodulation algorithm and w_l are the complex weighting factors.

Equation (11) can be written in the frequency domain because discrete Fourier transforms are linear operators. The frequency domain expression is: [15]

$$Y = \frac{\sum_{l=1}^{L} \widehat{H}_l^* R_l}{\sum_{l=1}^{L} \left|\widehat{H}_l\right|^2} \tag{12}$$

where $\widehat{H_l}$ are the channel frequency response estimates for OFDM subcarrier l and R_l are the received subcarriers' data. The denominator provides the normalization to the root mean square of the signal amplitude in the numerator [15]. Equation 12 implies that

MRC performs equalization. However, when tests were performed without MRC, a separate equalization function was used [2].

In this thesis the same data was repeated over various numbers of the 192 available data subcarriers. The received signals were then combined using MRC at the receiver. This thesis conducted its study repeating the data on all 192 data subcarriers, on 96 data subcarriers and on 48 data subcarriers.

D. SUMMARY

This chapter discussed the different modulation methods used by 802.16a. The standard can use either a single carrier mode, OFDM or OFDMA. The single carrier mode is supported by a higher per-carrier data rate to make up for its lack of parallel data subcarriers. The OFDM and OFDMA are scalable and can support different numbers of users.

Additionally, the terms and concepts central to choosing accurate channel models were presented. Rayleigh fading, without a direct signal path, is used to model the worst case scenario, which is no line of sight path with many significant multipaths. This is in addition to AWGN which is always present. The channel is slow fading due to the fixed locations of the BSs and the SSs. This can be shown by comparing the coherence time and the symbol time. The coherence time was found to be approximately $T_C = 9.1x10^{-4} s$ for a likely center frequency and $T_C = 4.15x10^{-4} s$ for a worst case scenario. The symbol time can be approximated as $T_S < 10^{-6} s$, resulting in $T_C >> T_S$ for either coherence time. This study's main focus is the performance of 802.16a modeled in a Rayleigh fading channel. The next chapter presents the results as well as the analysis of 802.16a tested in various environments. The tests are described as well as the meaning of the results.

THIS PAGE INTENTIONALLY LEFT BLANK

III. PERFORMANCE ANALYSIS OF PARTIAL BAND JAMMING AGAINST 802.16A

A. OVERVIEW

The results of this chapter will be broken up into two categories:

- MRC in AWGN with broadband and narrowband unintentional interference
- MRC in AWGN with broadband and narrowband intentional interference

In this experiment a broadband interference source refers to sources that cover all 200 user subcarriers whereas narrowband interference sources cover only some of the data subcarriers. Experiments were conducted using interference signals overlapping 25, 50, 100 and all 200 of the used data subcarriers.

Unintentional interference signals were added to the channel to test the performance of diversity with MRC techniques if the 802.16a system was operating in an environment with either narrowband or broadband signals which is very likely. It is expected that diversity with MRC will dramatically improve the performance. The graphs in the unintentional interference section display the SIR level for each affected channel. The experiments with intentional interference signals tested the system with MRC if someone was intentionally interfering in an effort to disrupt communications. An explanation of intentional interference is offered later.

All simulations were run with a Rayleigh fading channel with a RMS delay spread of $50\,ns$. Testing with a RMS delay spread of 50 *ns* simulates conditions in an indoor environment. Larger RMS delay spread values are a better simulation of an urban environment. [11]

B. SIGNAL PERFORMANCE IN AWGN WITH BROADBAND AND NARROWBAND INTERFERENCE WITHOUT MRC

Testing the performance of the signal in an environment containing AWGN with broadband and narrowband interference is the most realistic conditions for testing. Whether this network is used in the commercial sector or in military operations, there will always be white noise and mostly likely broadband and narrowband interference as well. Knowing the capabilities and limits of this system operating in this environment is of utmost importance to the military where wireless communications are used on the battlefield to make important decisions and relay sensitive information.

For each experiment, it was assumed there was a noise floor 20 dB below the signal level. Then, for each of the data rates, the different levels of MRC were tested with additional partial band interference. The additional interference was bandlimited white noise and was added in 25, 50, 100 and all 200 of the used subcarriers. It was assumed the signal to interference level was constant across all interference-corrupted subcarriers. Additionally, it was assumed that the total interference power is directly proportional to the number of subcarriers undergoing interference. The MATLAB® simulation measured the signal power and then adjusted the magnitude of the interference signal to correctly represent the desired SIR values.

A number of details about the simulations must be discussed. For each E_b / N_i tested, 10,000 packets were transmitted. The program formed the packets with random data then sent the data through the channel where noise was added. Finally, the packets were received and each packet was compared to the original packet sent. To determine the P_b, or bit error rate, all the bit errors were summed for each E_b / N_o, then divided by the number of total bits sent. A packet was categorized as in error if any single bit was an uncorrected error. Similarly to the P_b, the packet error rate (PER) was determined for each E_b / N_o by summing the packet errors and dividing by the total number of packets sent. The packet length depended upon the amount of repetition and the number of DL bursts. Similar packet lengths were desired despite the amount of repetition as PER depends on the packet length. For MRC = 192, there were two DL bursts, for MRC = 96

there were four DL bursts, for MRC = 48, there were eight DL bursts and for MRC = 1 there were also eight DL bursts. The exception to the pattern for DL burst length was made for MRC =1 to have DL bursts = 8 instead of 384 due to simulation time constraints.

1. Unintentional Interference

The first six figures will show the effects of unintentional interference on 802.16a with a constant data rate and modulation scheme and no MRC. The data rate values of 12 Mb/s, 36 Mb/s and 54 Mb/s were chosen to represent the lowest value, the highest value and a value in the middle of the range. In the upcoming figures, PBI = 25, 50, 100 or 200 refers to partial band jamming being applied to 25, 50, 100 or 200 of the subcarriers.

a. Constant Data Rate and Modulation Scheme Plots

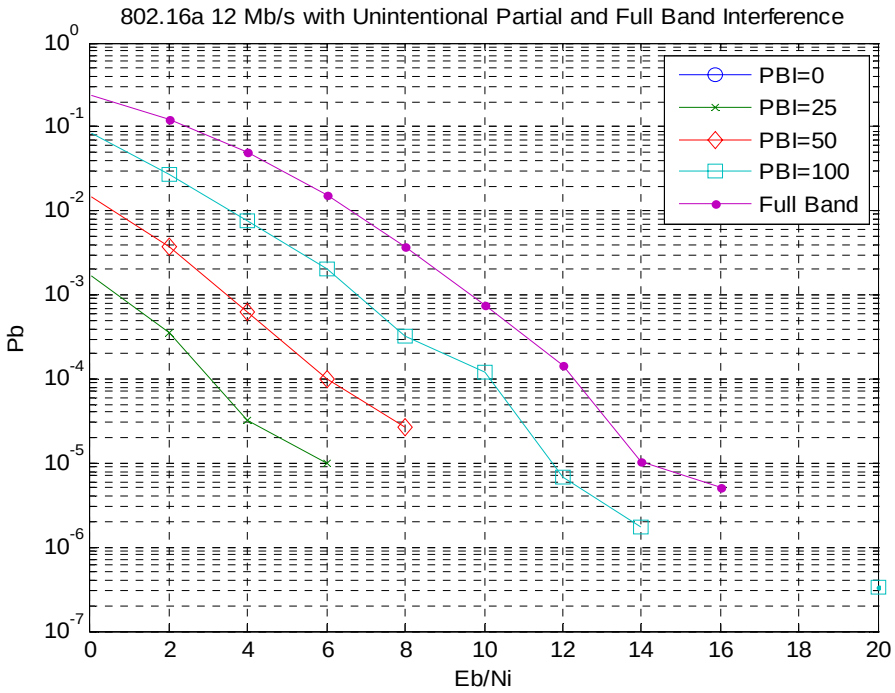

Figure 9 12 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

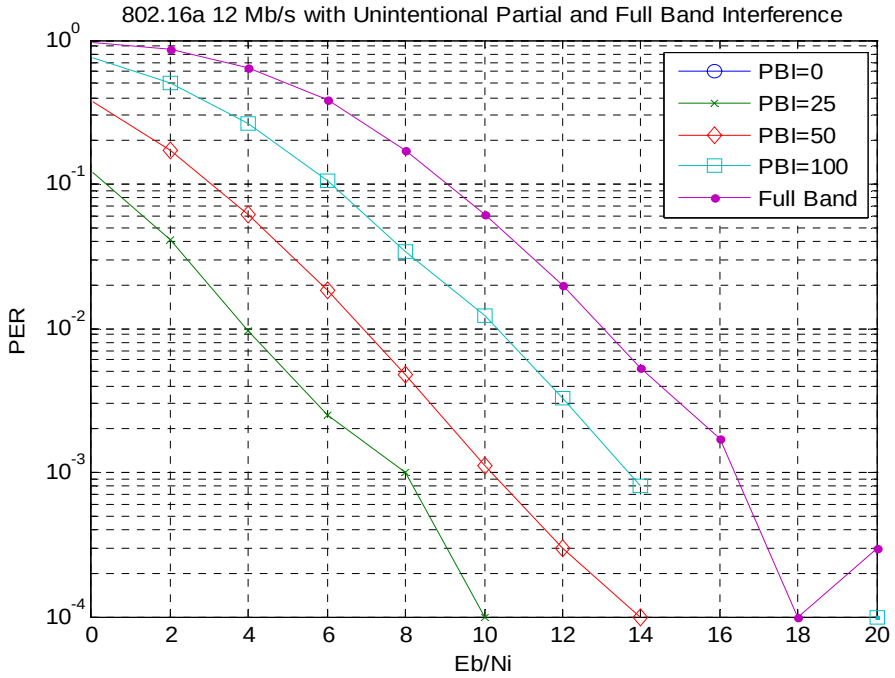

Figure 10 12 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

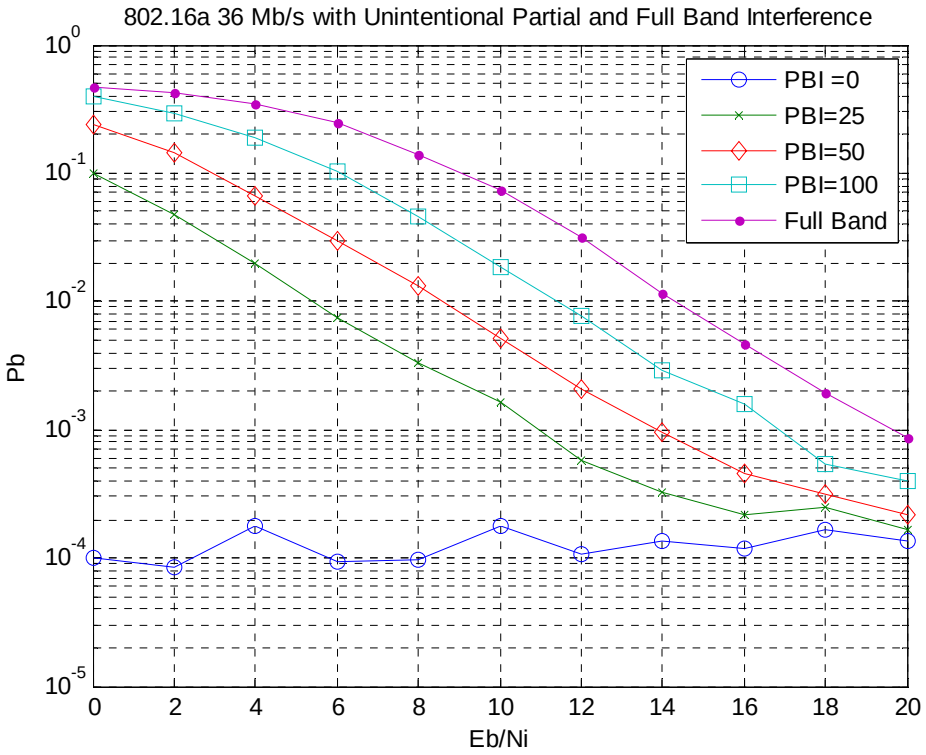

Figure 11 36 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

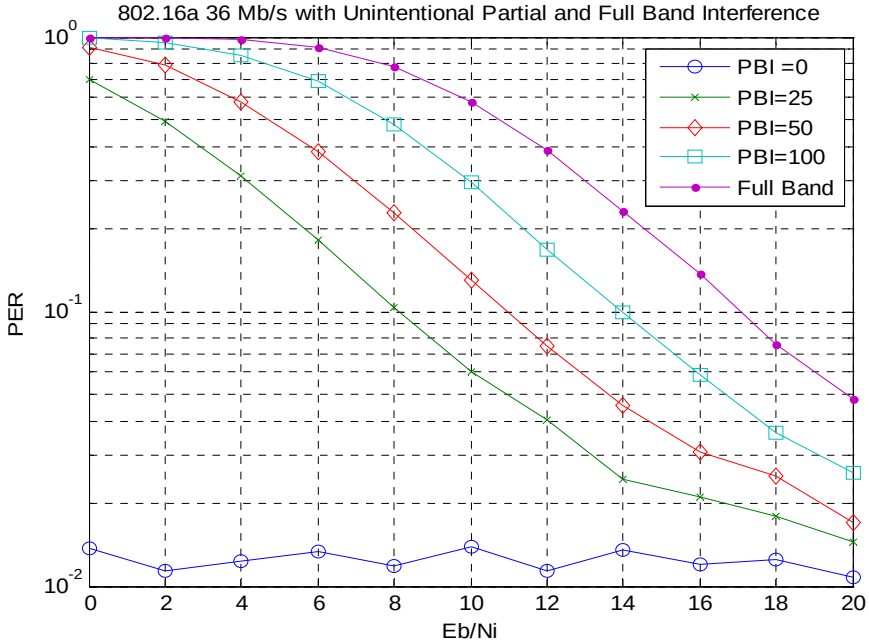

Figure 12 36 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

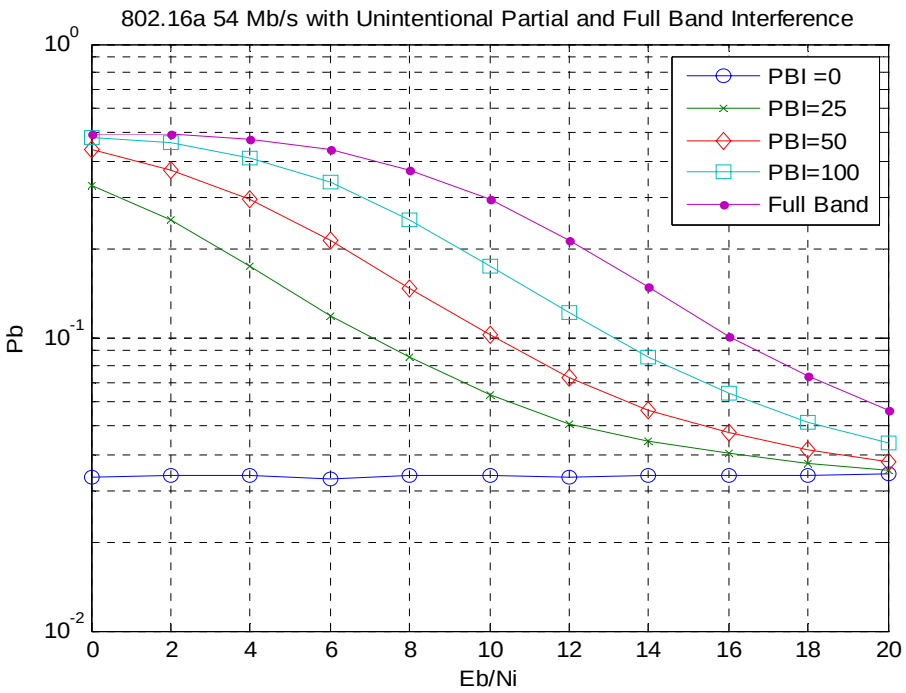

Figure 13 54 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

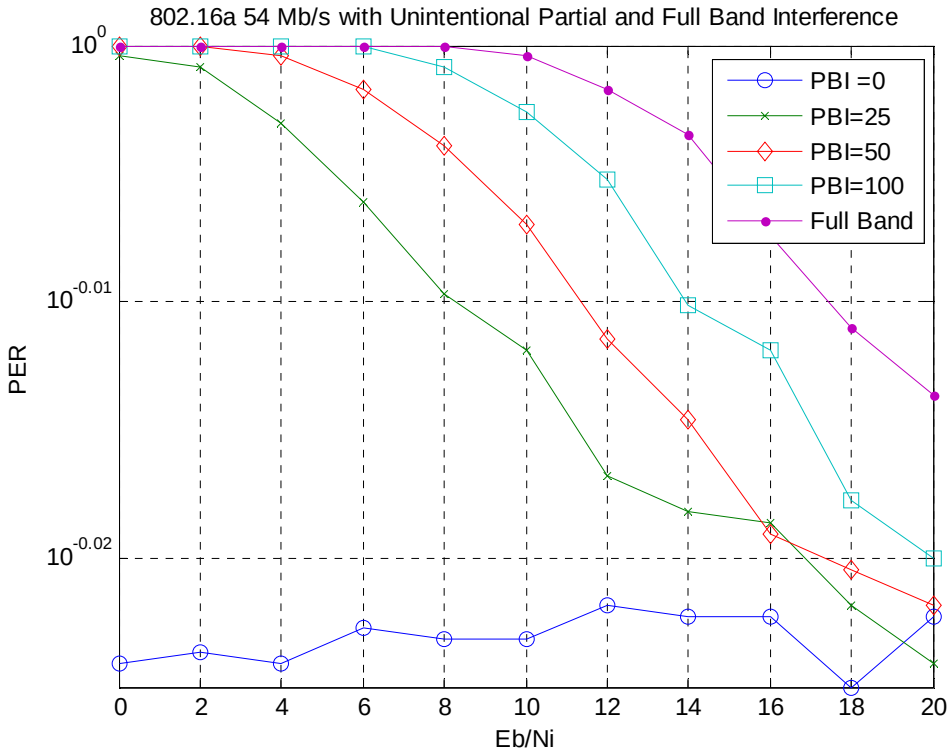

Figure 14 54 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

In Figure 9 through Figure 14, the results of unintentional interference all approach the horizontal line from the data of PBI = 0 and SNR = 20 which represents the P_b or the PER with no interference and an SNR = 20 dB. It is expected that if the SIR ratio goes to 20 dB, the performance will meet the performance for AWGN only because as SIR increases past 20 dB, the AWGN will be the primary source of noise as the interference strength decreases. The plotted lines would become level and remain constant at the P_b due to AWGN only. Also, signals with fewer subcarriers affected by the unintentional interference have a much lower P_b and PER for a given SIR. It is expected that as the amount of interference decreases, the P_b will be lower. It should be noted that in Figure 14 there is an approximate PER of 1 under all conditions. This demonstrates that without a higher SIR, the increased data rate of 54 Mb/s is useless due to the poor performance.

In the above figures as well as the following figures, some curves have more points than others because when a data point was equal to zero, P_b = 0 or PER = 0, it did not plot due to the logarithmic scale used for the Y-axis in all plots. This explains why some curves have a different range of E_b/N_i than others and why in certain figures the legend describes four curves yet only two or three are apparent. The other two curves were all zero and did not plot.

Unintentional interference is a very likely source of interference. An application of this testing would be to evaluate a wireless communication system in a NLOS environment with a lot of interference but no intentional interference. An example of this would be a battlefield in which the enemy is not attempting to jam the signal.

The following eight figures, Figure 15 through Figure 22 show the same data as the previous six but displayed differently. These figures highlight the effects of one level of PBI on all of the data rates whereas the previous figures showed the effects of different levels of PBI on one data rate.

b. Constant Level of Partial or Full Band Interference Plots

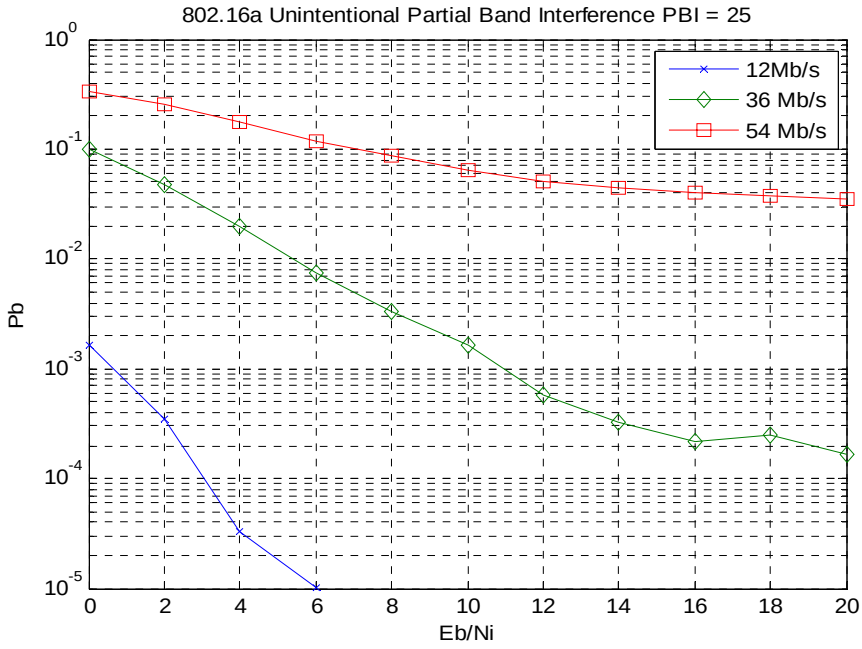

Figure 15 PBI=25, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate.

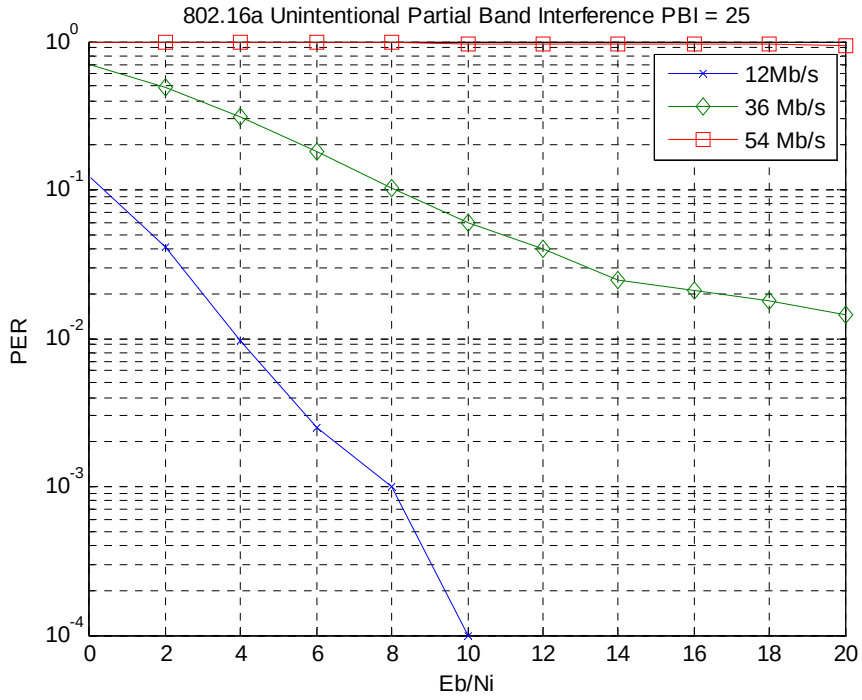

Figure 16 PBI=25, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate.

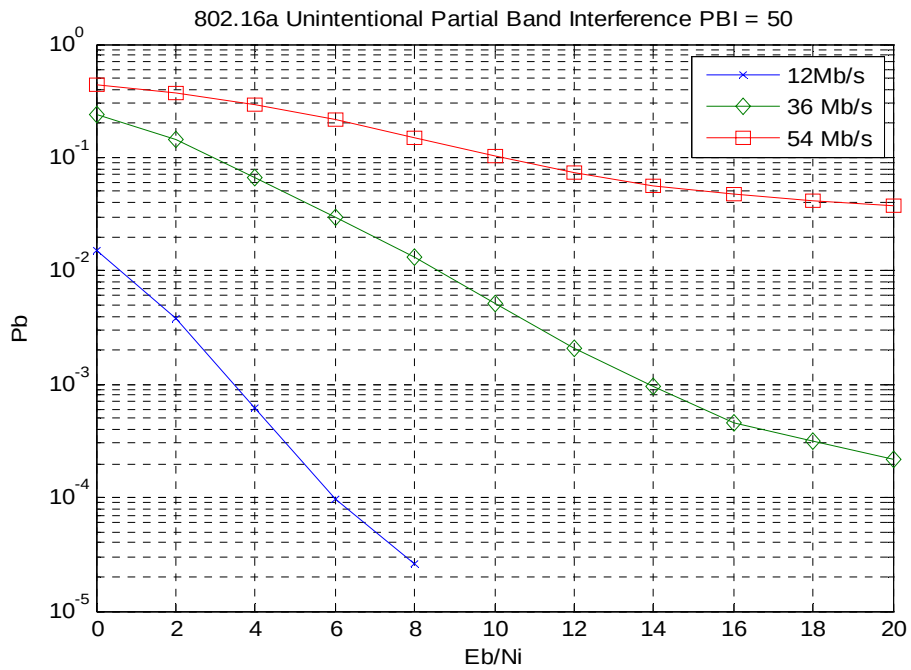

Figure 17 PBI = 50, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate.

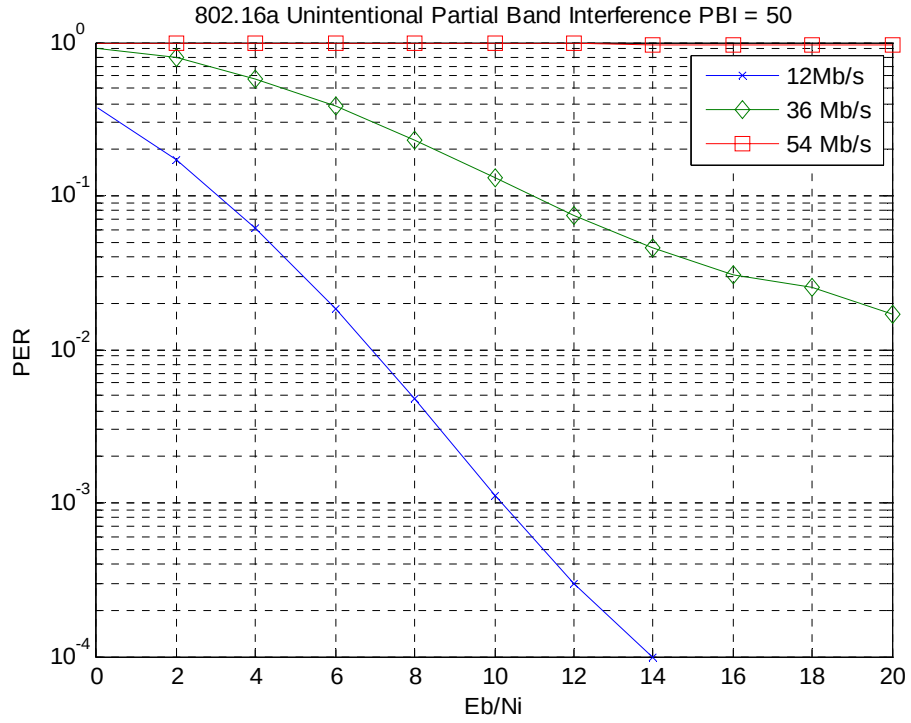

Figure 18 PBI = 50, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate.

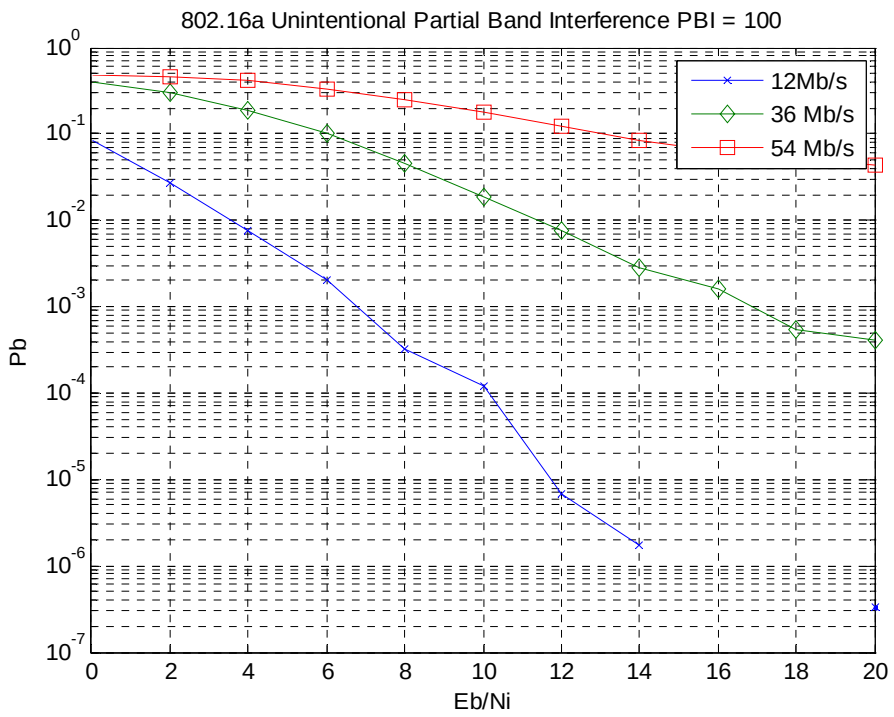

Figure 19 PBI = 100, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate.

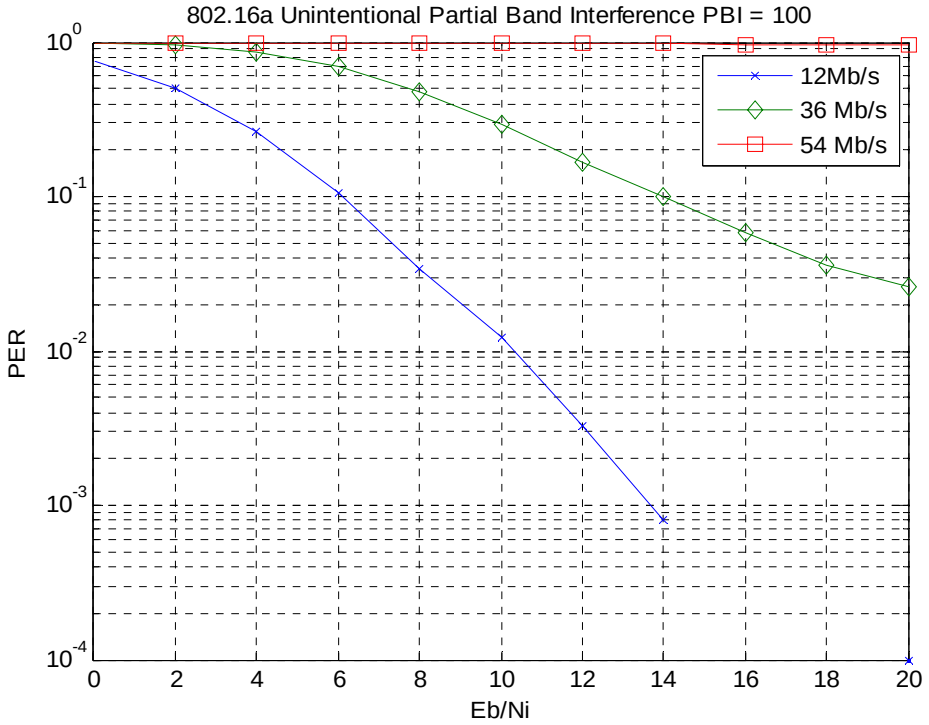

Figure 20 PBI = 100, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate.

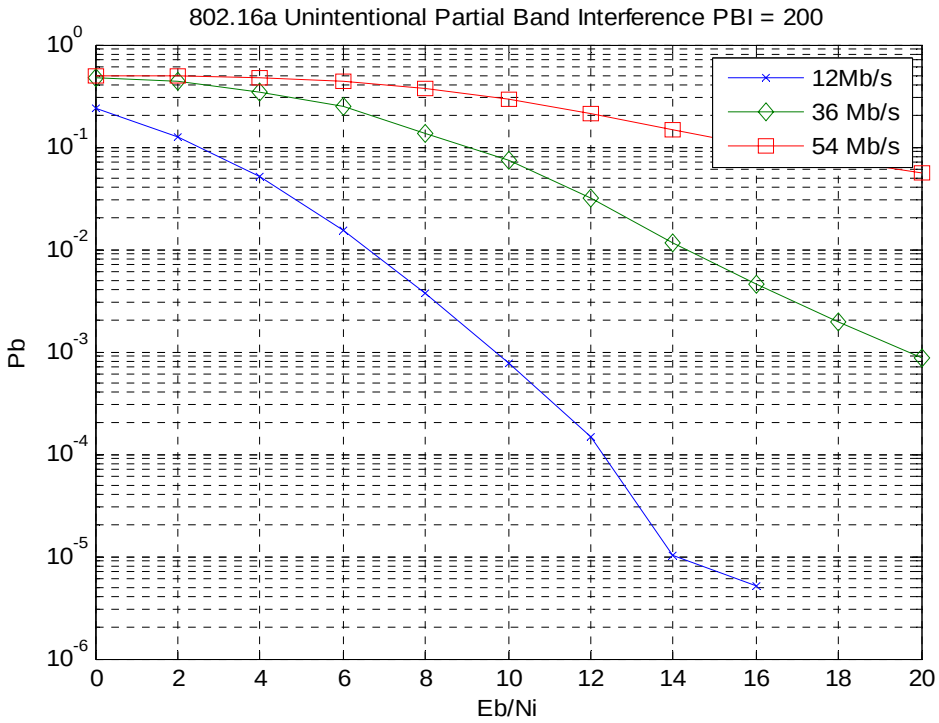

Figure 21 PBI = 200, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate.

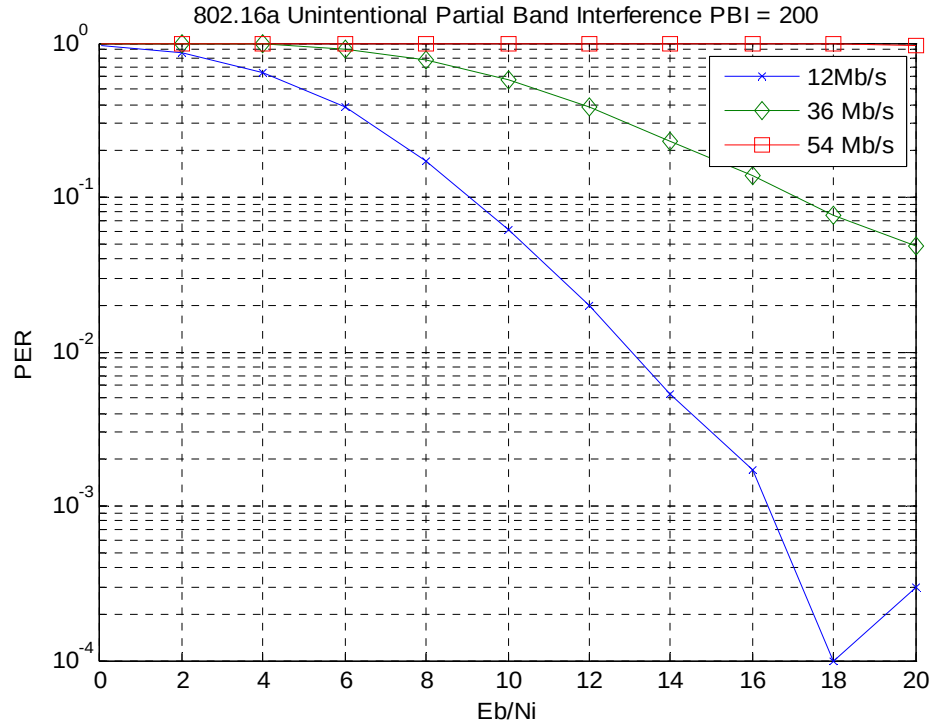

Figure 22 PBI = 200, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is the data rate.

Unintentional interference, both partial and full band, negatively affects the performance of the different data rates and modulation schemes approximately the same. It is expected that there is no large difference in effect from one data rate to the next as they are all equally interfered with and it should affect them similarly. This can be shown by looking at Figure 15 and Figure 19. All three data rates experience approximately a 6dB decrease in performance from PBI = 25 to PBI = 100. This makes sense because there was a quadrupling of the interference power and subsequent a 6dB decrease. Looking at Figure 17 for the change from PBI = 25 to PBI = 50, there was approximately a 3dB decrease in performance as the interference doubled. The performance is better with a lower data rate regardless of the added interference.

2. Intentional Interference

The previous sets of figures showed the effects of unintentional interference on 802.16a communications. The intentional interferer has a set amount of power that must be split across the subcarriers whereas the unintentional interferer has the same amount of power per channel regardless of how many subcarriers. The amount of power per subcarrier in an intentional interferer is inversely proportional to the number of subcarrier with interference. For example, an intentional interferer can focus 10 watts on one subcarrier, 1 watt on 10 subcarriers or 0.05 watts on 200 subcarriers. However in the case of unintentional interference, there would be 1 watt on each subcarrier leading to 1 watt of interference for one subcarrier, 10 watts of interference for 10 subcarriers and 200 watts of interference for 200 subcarriers. The following plots, Figure 23 through Figure 28, represent the effects of intentional interference with no MRC used. The legends describe PBI because it is still partial band interference. The difference between intentional and unintentional interference is how the interference power is calculated. An application of this type of interference is a military wireless communication system used in battlefield setting where the enemy has established jamming devices and could raise the power of the jamming signal. The enemy could continue to increase the interference power to disrupt the signal.

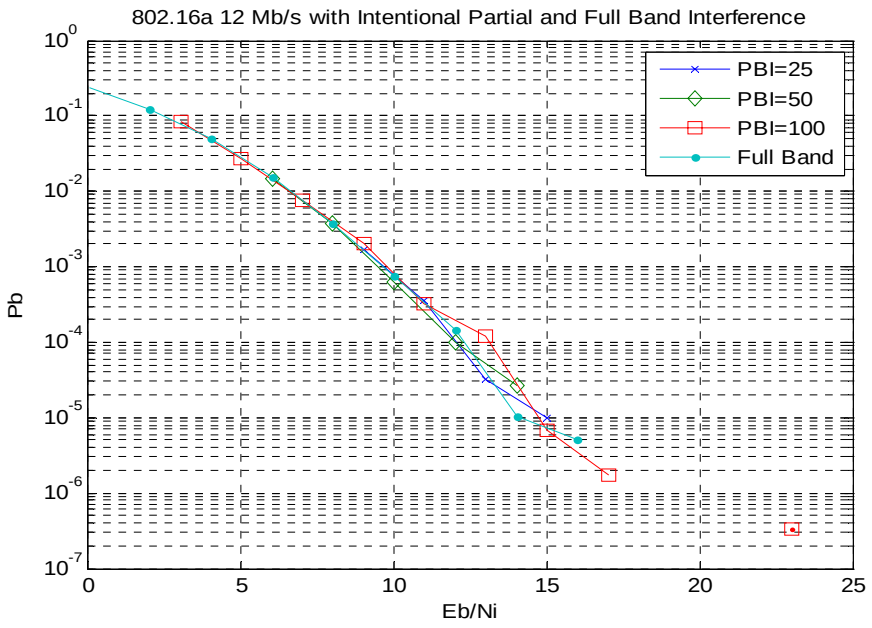

Figure 23 12 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed.

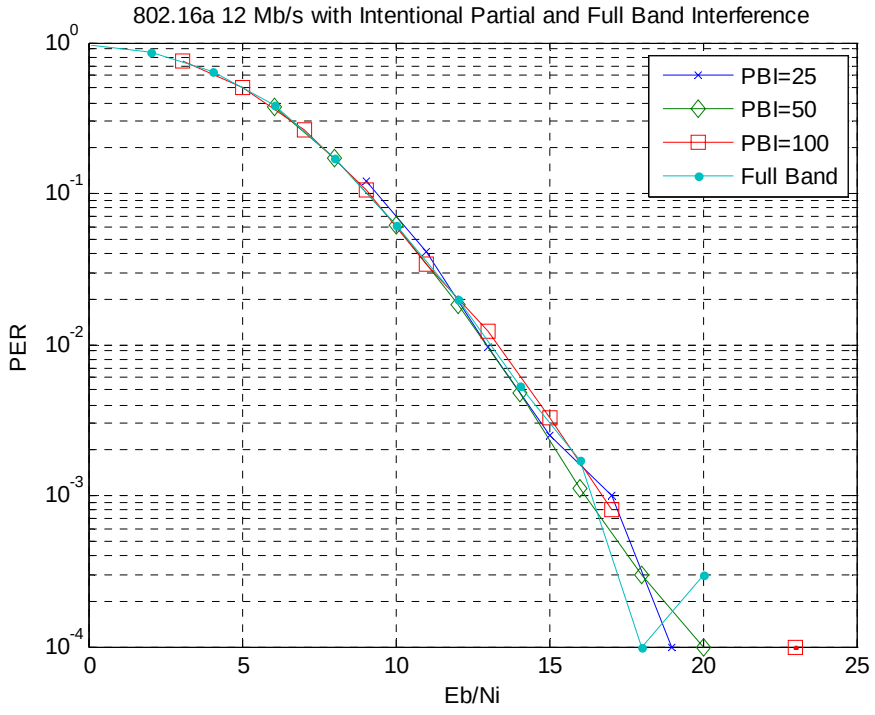

Figure 24 12 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed.

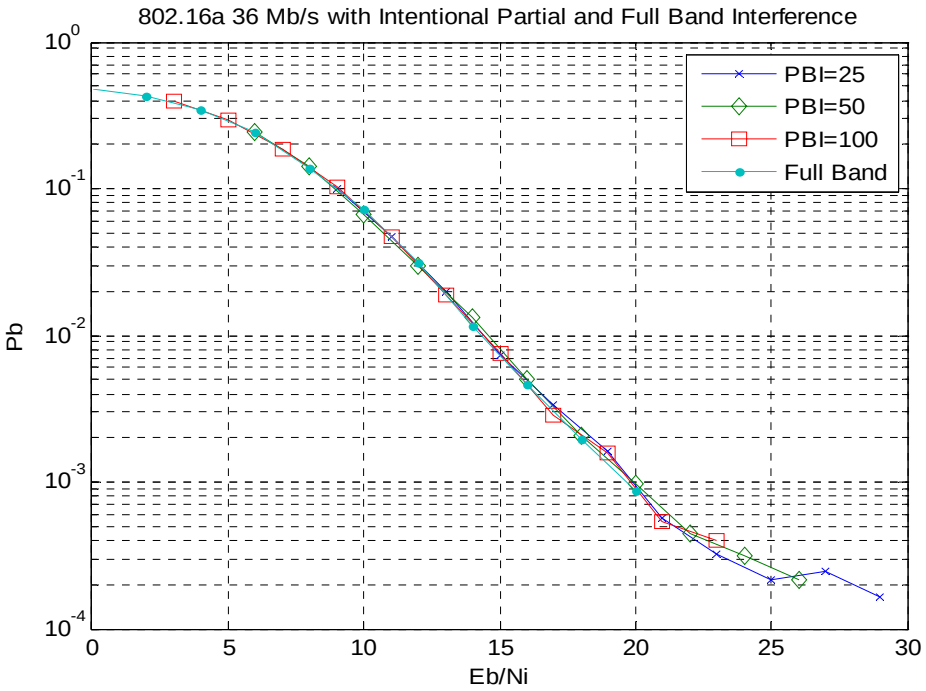

Figure 25 36 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed.

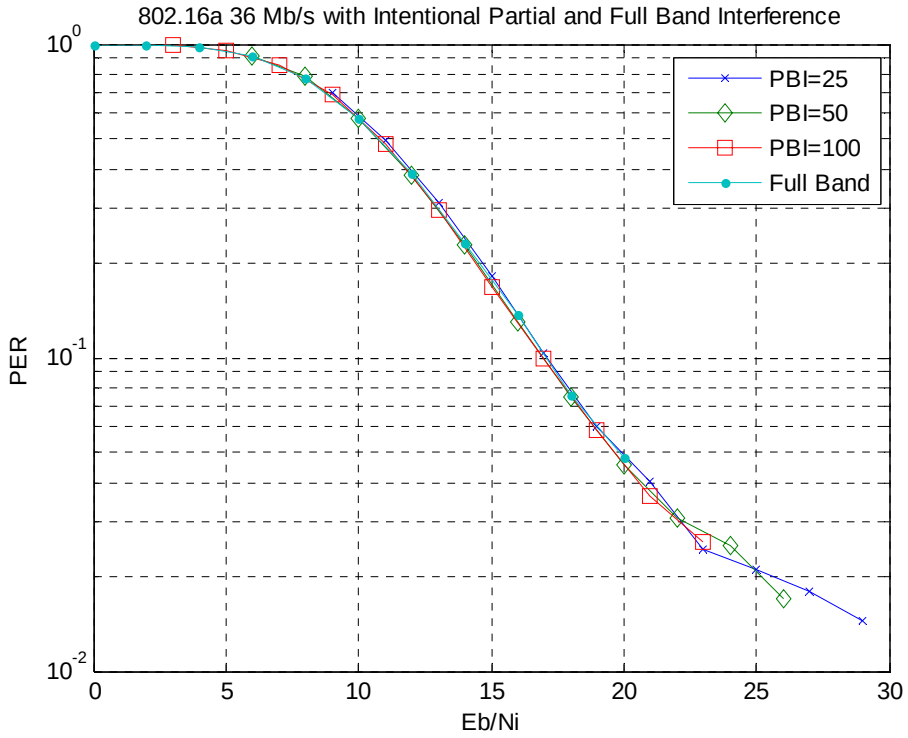

Figure 26 36 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed.

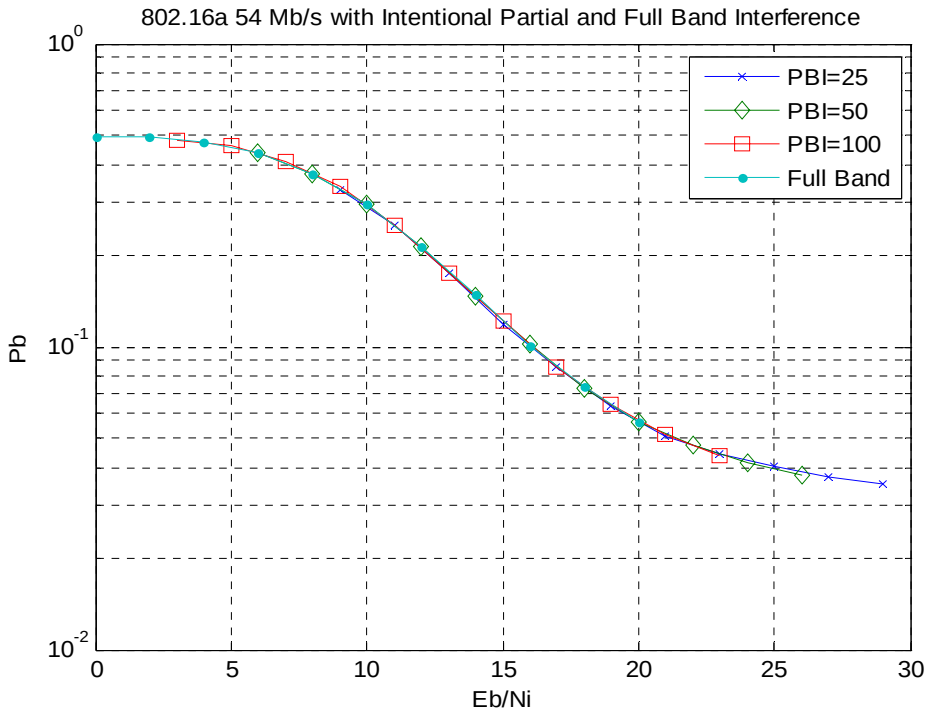

Figure 27 54 Mb/s, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed.

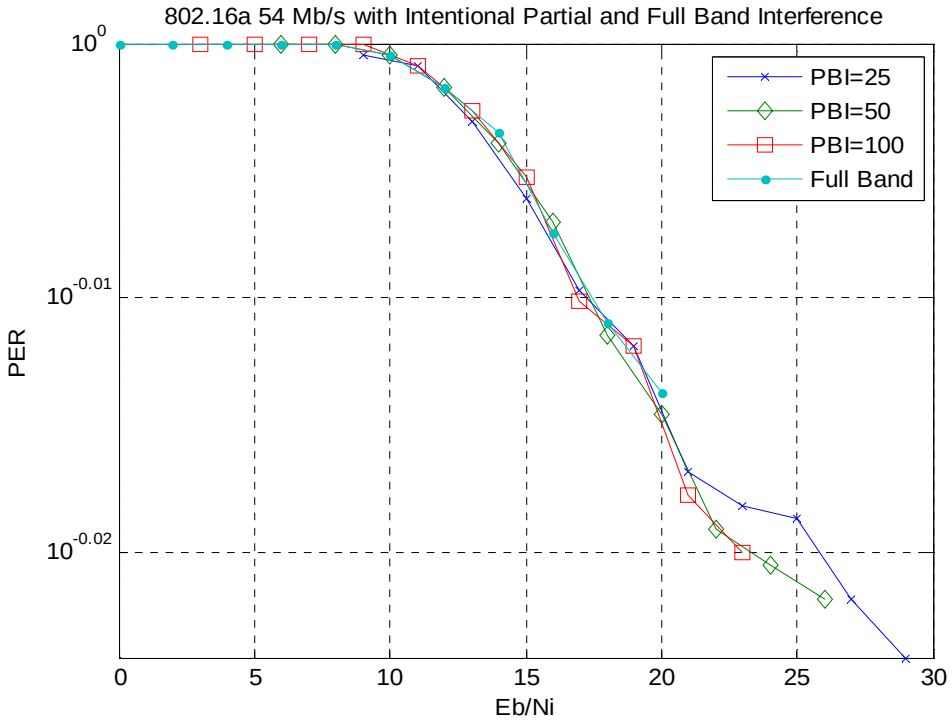

Figure 28 54 Mb/s, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of jamming. Parameter is number of subcarriers jammed.

Through careful observation of the data in Figure 23 through Figure 28, it is readily apparent that partial band intentional interference and full band intentional interference have the same effect on an 802.16a signal. This shows that the location of the interference in the band is not important but rather the overall strength of the interference relative to the signal power. This robustness to the location of the noise can be attributed to the scrambling and interleaving process used in 802.16a. The scrambling and interleaving techniques spread the errors across the signal making them look more like random errors instead of being specifically caused by the narrow band interferer. The final result is that narrow band interference affects the network in the same manner as broadband noise.

Additionally as shown in Figure 28, 54 Mb/s is essentially worthless regardless of the interference.

C. SIGNAL PERFORMANCE IN AWGN WITH BROADBAND AND NARROWBAND INTERFERENCE WITH MRC

To explore the effects of MRC in the presence of an interferer signal, simulations were run using 54 Mb/s and 12 Mb/s. These two data rates were chosen because they represent the extremes of the data rate spectrum. 54 Mb/s provide the highest data rate and worst reliability, while 12 Mb/s provides the lowest data rate and best reliability. Testing the system in AWGN with broadband and narrowband interference simulates any type of realistic setting. Regardless of where the system will be used, there will be AWGN and narrowband interference will likely be present. These tests simulate a potential military communication system in a harsh setting such as an urban environment with many buildings and many sources of interference. This is very applicable as war is increasingly waged in dense urban areas as opposed to wide open spaces.

In the figures below, the MRC is varied. A value of MRC = 1, or L = 1, signifies there is no repetition or MRC and so different data is transmitted on every subcarrier. MRC = 48, or L = 48, signifies that the subcarriers are divided into four groups of 48 while MRC = 96, or L = 96, represents the subcarriers divided into two groups of 96.

The subcarriers in a group transmit the same data but each group transmits different data. Lastly MRC = 192, or L = 192, means that all 192 subcarriers transmit the same data.

The data rates listed in the figures represent the data rates including the repeated bits. The actual data rates are the listed data rate divided by the amount of repetition used. In the E_b / N_o in the following figures, the E_b is the energy per transmitted bit. The energy per data bit is the energy per transmitted bit times L, the number of times each bit is repeated.

1. 54 Mb/s, Constant MRC with Unintentional Interference

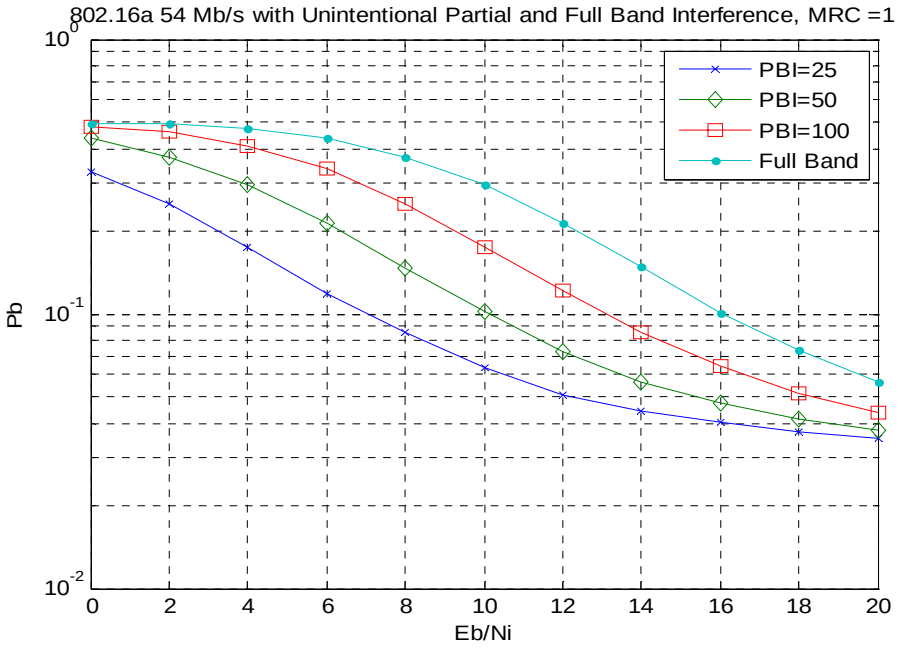

Figure 29 54 Mb/s, MRC =1, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

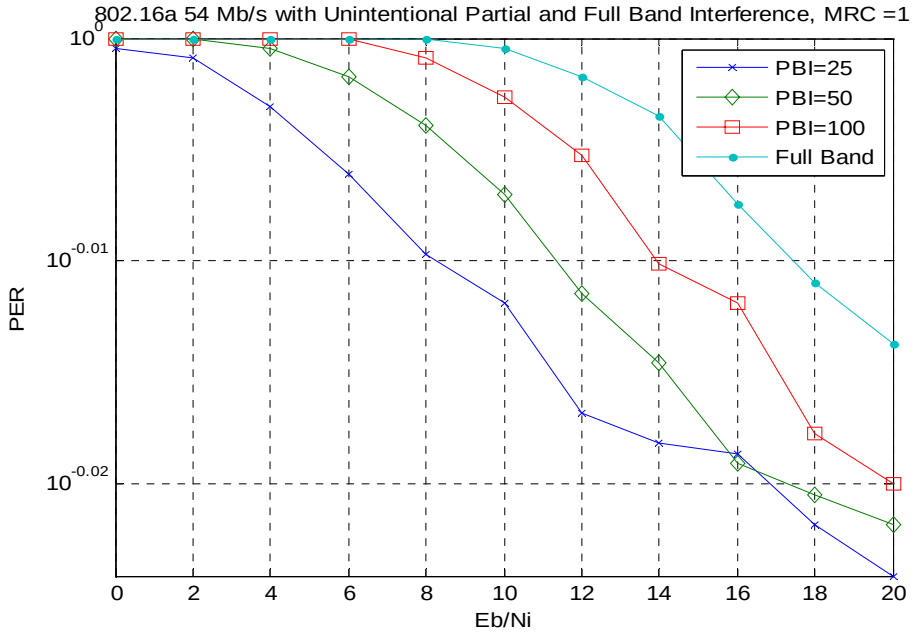

Figure 30 54 Mb/s, MRC =1, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

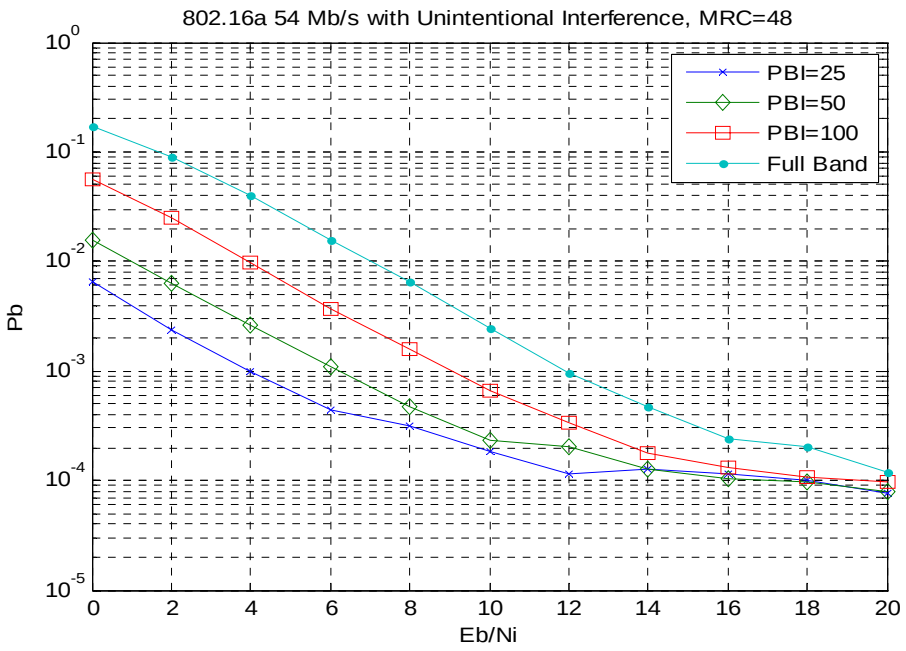

Figure 31 54 Mb/s, MRC =48, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

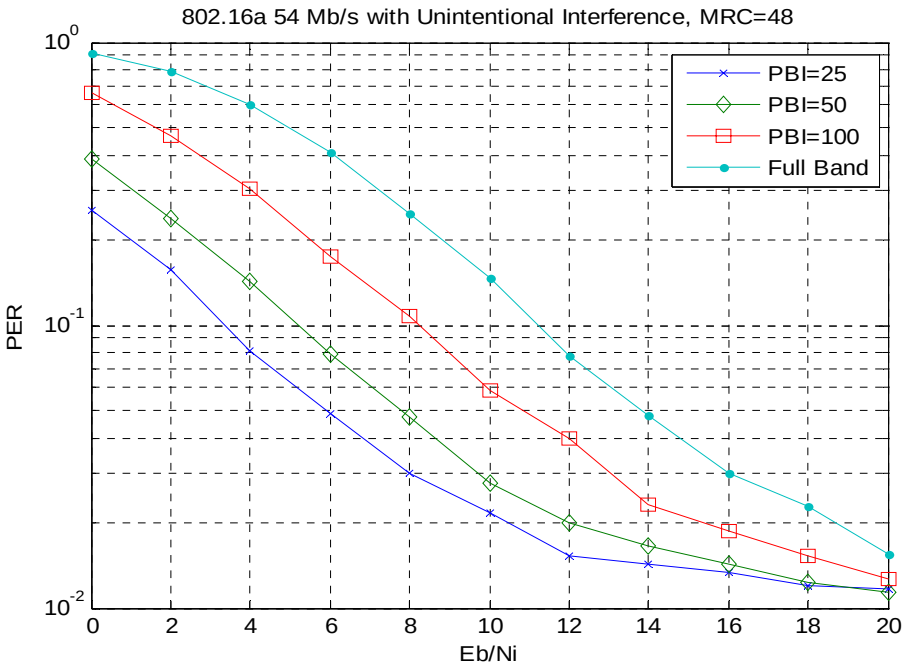

Figure 32 54 Mb/s, MRC =48, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

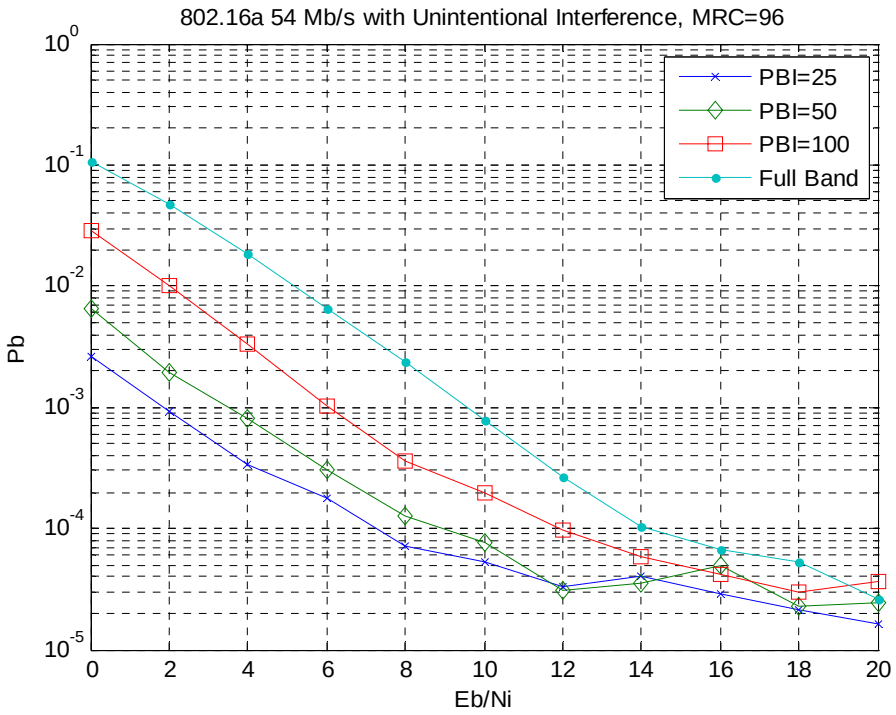

Figure 33 54 Mb/s, MRC =96, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

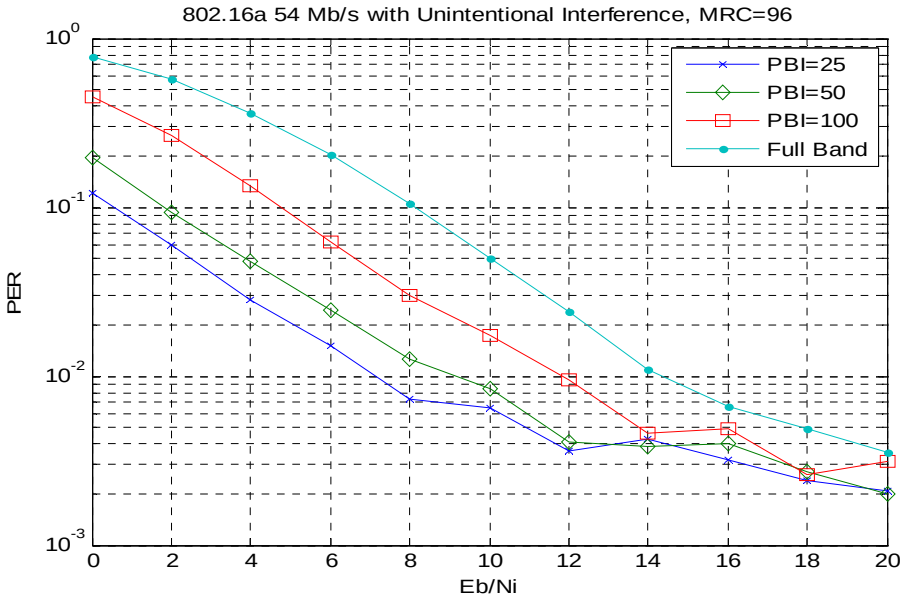

Figure 34 54 Mb/s, MRC =96, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

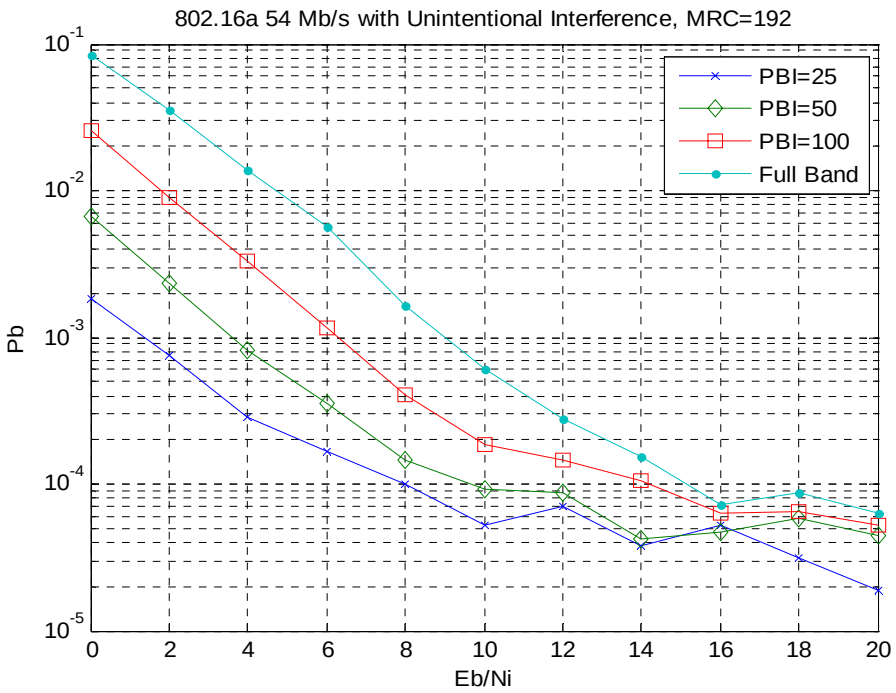

Figure 35 54 Mb/s, MRC =192, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

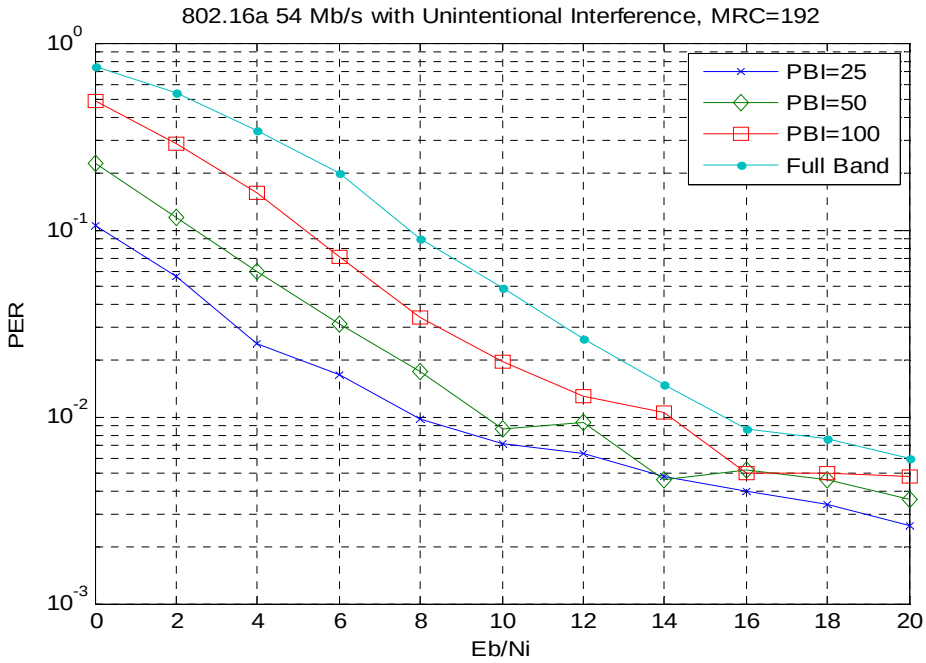

Figure 36 54 Mb/s, MRC =192, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

In Figure 29 through Figure 36, the performance of MRC in a range of unintentional interference was observed. This was accomplished by holding the MRC constant and varying the amounts of PBI. In each graph, the horizontal separation of the lines is roughly 3 dB. This amount holds with the assumptions as to what constitutes unintentional interference. As the number of signals with interference doubles, along with it doubles the total amount of interference. Hence, the required SIR to maintain a constant P_b should be 3dB higher which is consistent with our findings. Figure 29 and Figure 30 were essentially repeated from Figure 13 and Figure 14 so that they could be more easily compared with the other values of MRC in this section.

2. 54 Mb/s, Constant PBI with Unintentional Interference

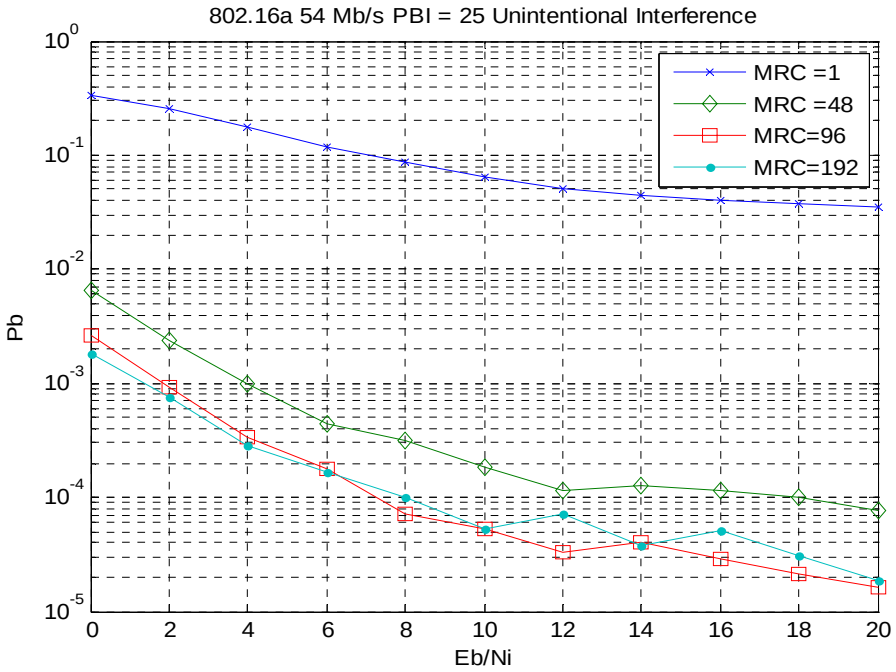

Figure 37 54 Mb/s, PBI = 25, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

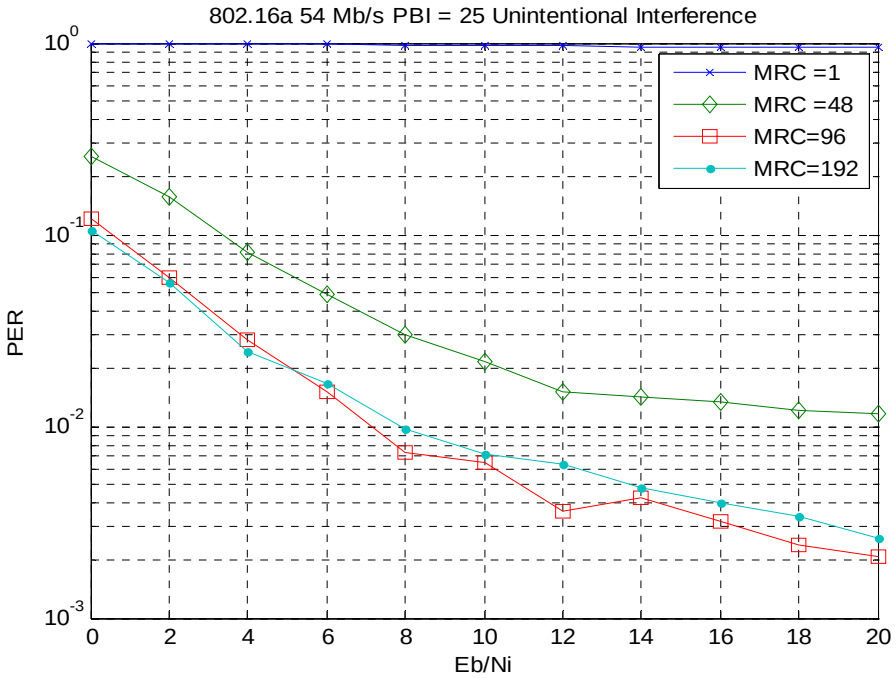

Figure 38 54 Mb/s, PBI = 25, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

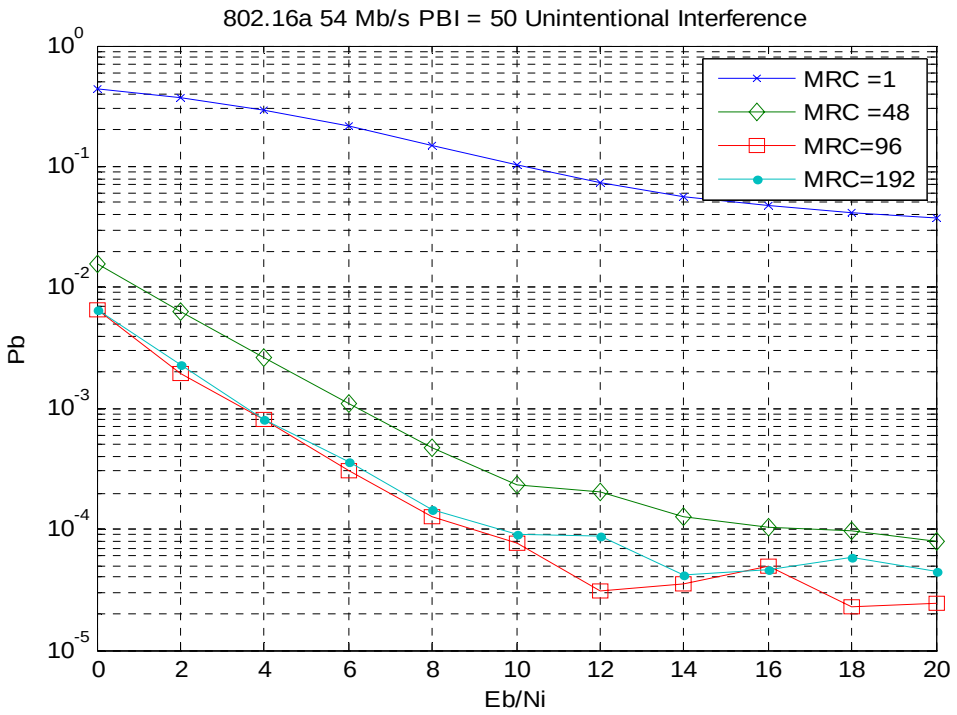

Figure 39 54 Mb/s, PBI = 50, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

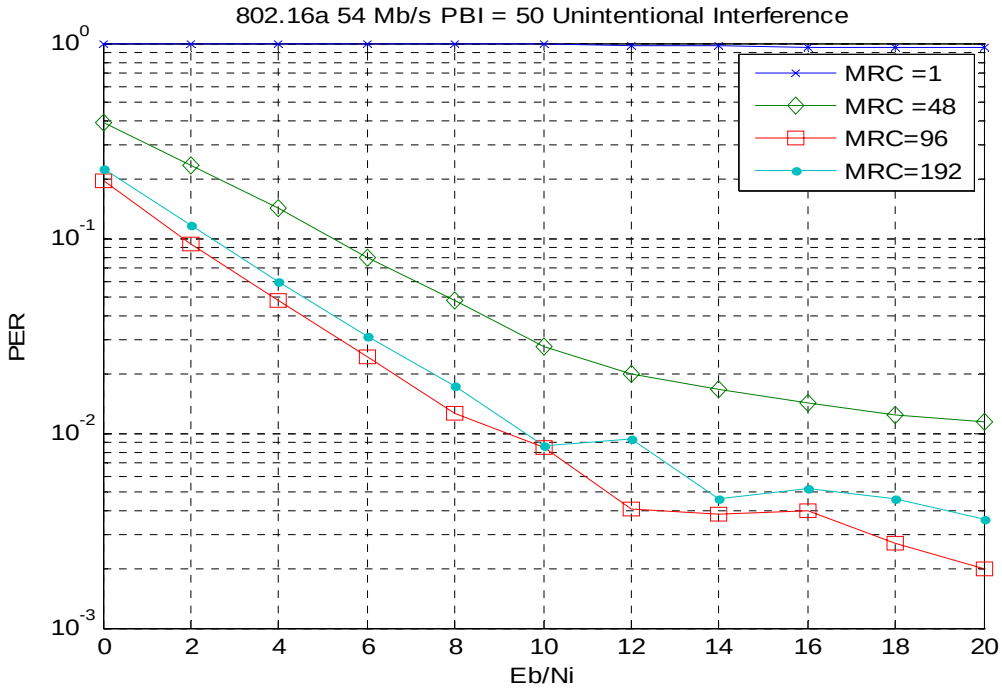

Figure 40 54 Mb/s, PBI = 50, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

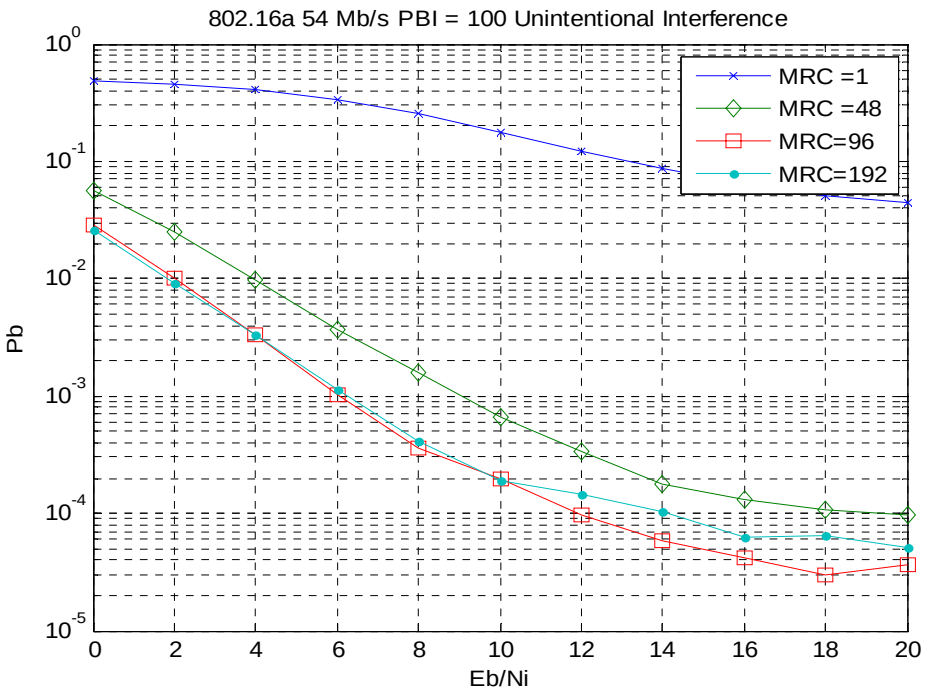

Figure 41 54 Mb/s, PBI = 100, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

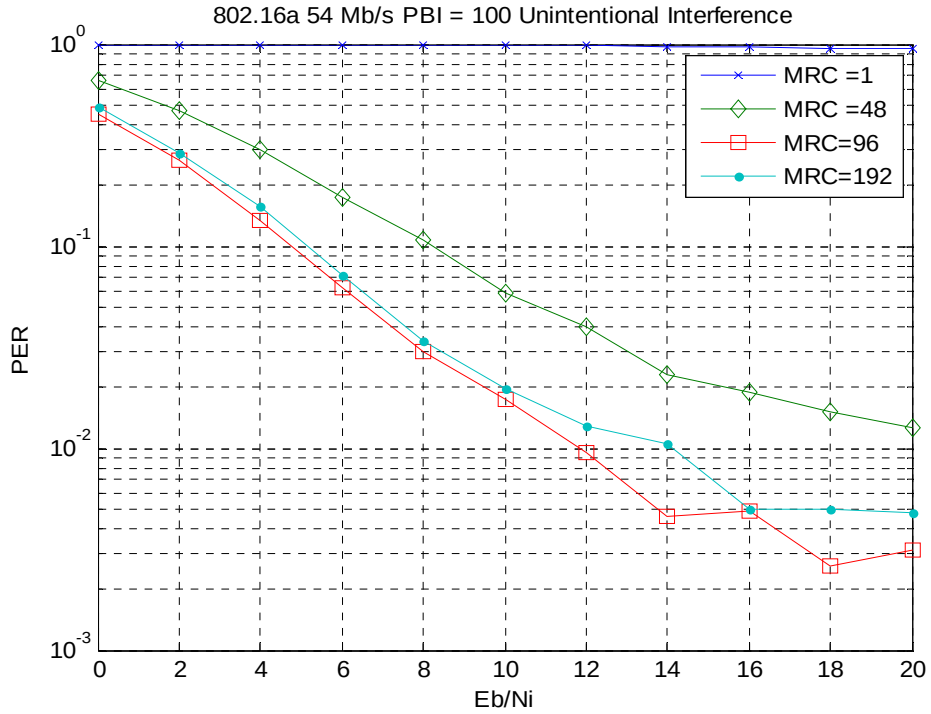

Figure 42 54 Mb/s, PBI = 100, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

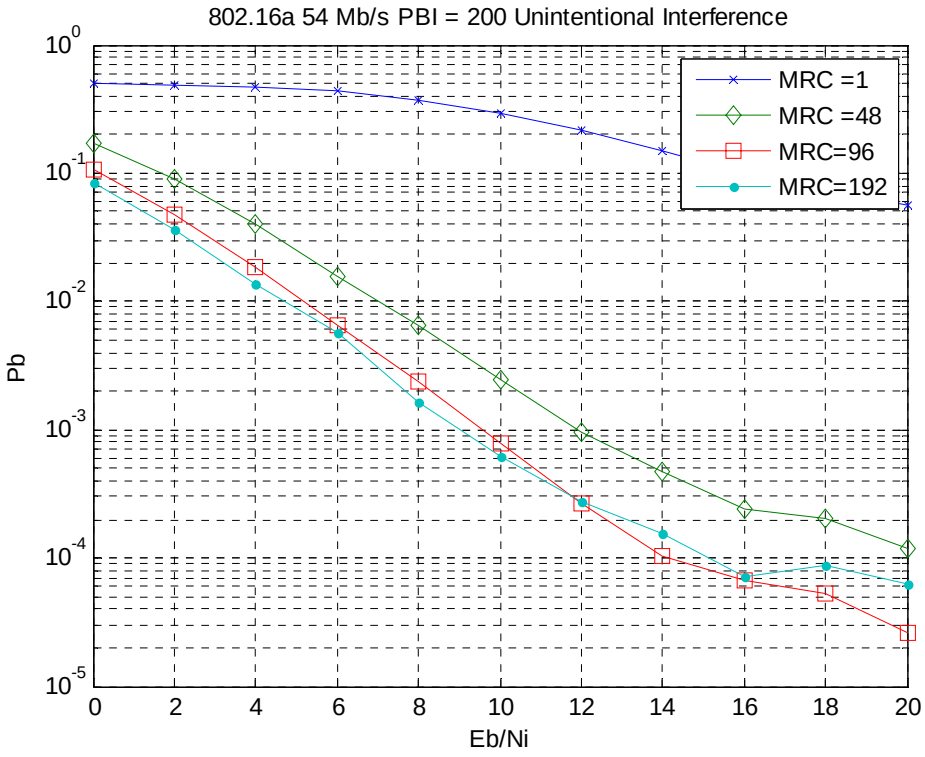

Figure 43 54 Mb/s, PBI = 200, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

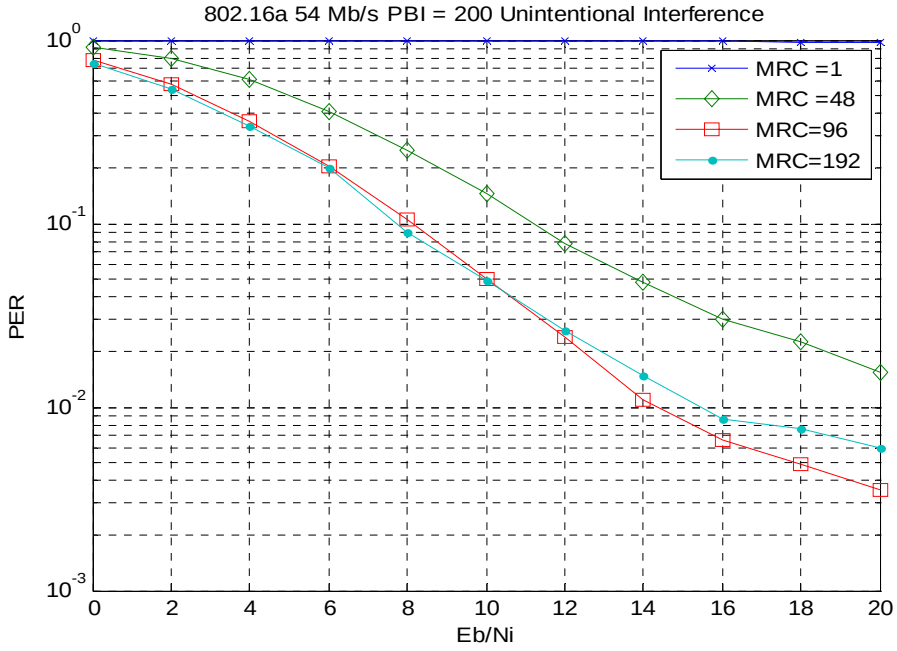

Figure 44 54 Mb/s, PBI = 200, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

The effects of MRC can be seen in Figure 37 through Figure 44. As the number of affected data subcarriers increases to 200 for full band interference, the effects of MRC are positive performance gains. In tests where there is less interference, such as a low power unintentional interference signal occupying a small percentage of subcarriers, it is observed that MRC has a much bigger impact. This is interesting and can be explained. With a relatively low power and low percentage of interference subcarriers, MRC is able to perform well because the signal is not too badly degraded. In more severe conditions MRC has a positive impact but it is not as great. Looking at Figure 45 with SIR =18dB, the advantage of MRC = 192 over MRC = 1 is approximately 18 dB.

In Figure 37 it can be seen that there is little gain from L = 96 to L = 192. This is because repeating the data 96 times is enough to offer any performance gains given through repetition and MRC. In Figure 40 L = 96 is distinctly better than L = 192 though not by a large margin. This trend can also be seen in Figure 42. A possible explanation is that L = 96 outperforms L = 192 in these examples for PER because while they have similar performance in terms of P_b, the packet length is slightly longer for L = 192 despite doubling the DL bursts for L = 96.

3. 12 Mb/s, Constant MRC with Unintentional Interference

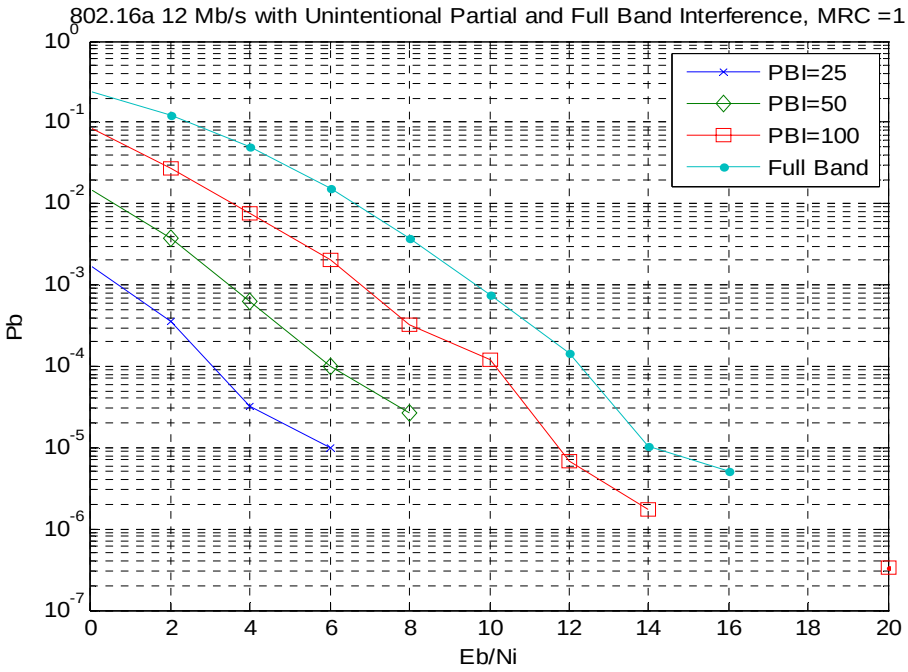

Figure 45 12 Mb/s, MRC =1, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

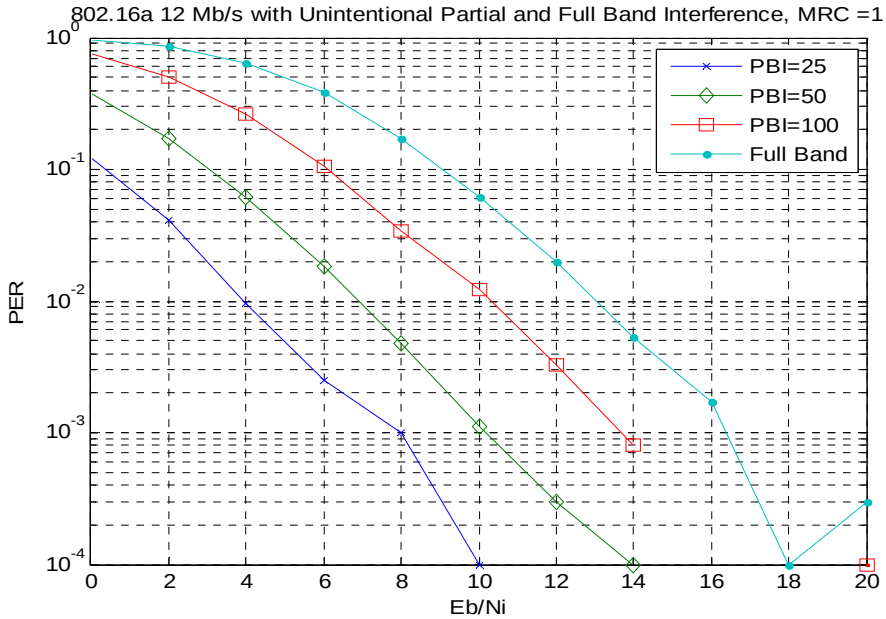

Figure 46 12 Mb/s, MRC =1, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

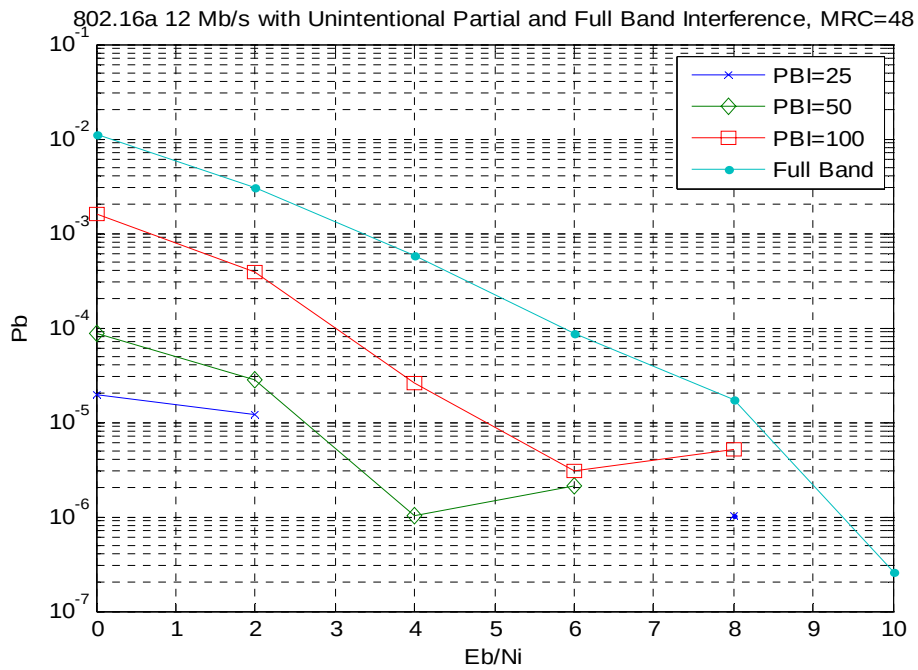

Figure 47 12 Mb/s, MRC =48, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

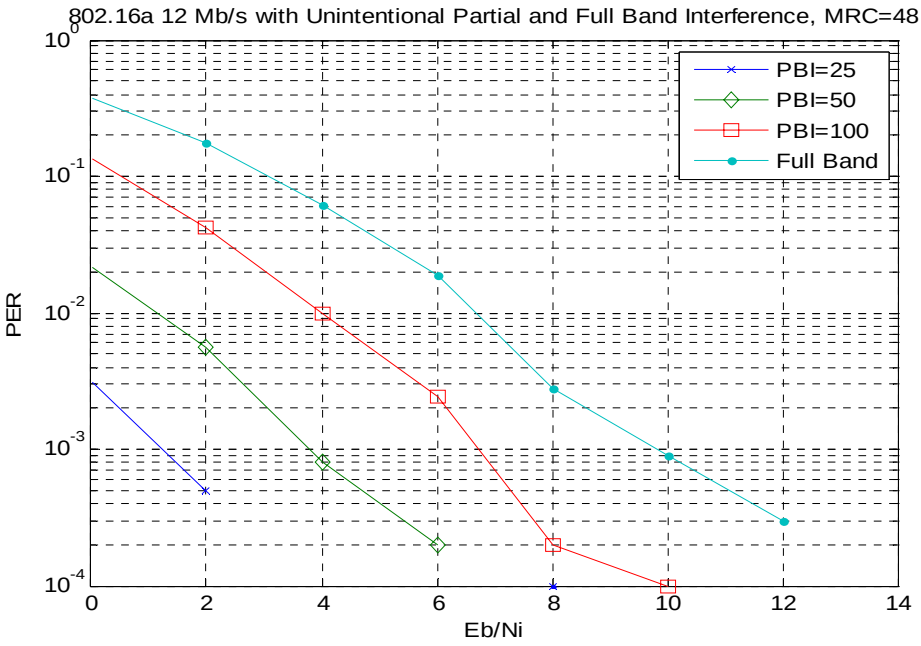

Figure 48 12 Mb/s, MRC =48, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

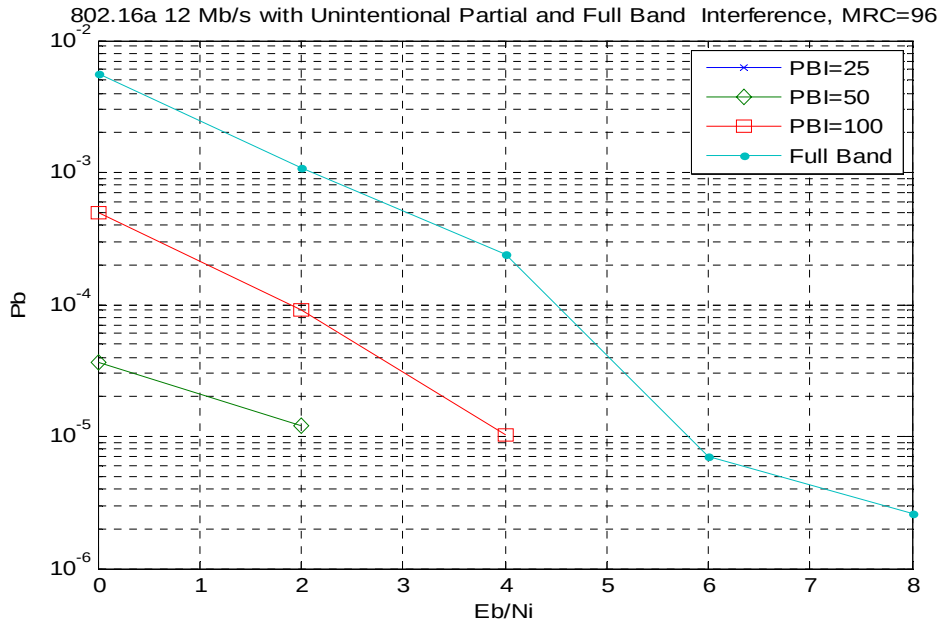

Figure 49 12 Mb/s, MRC =96, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

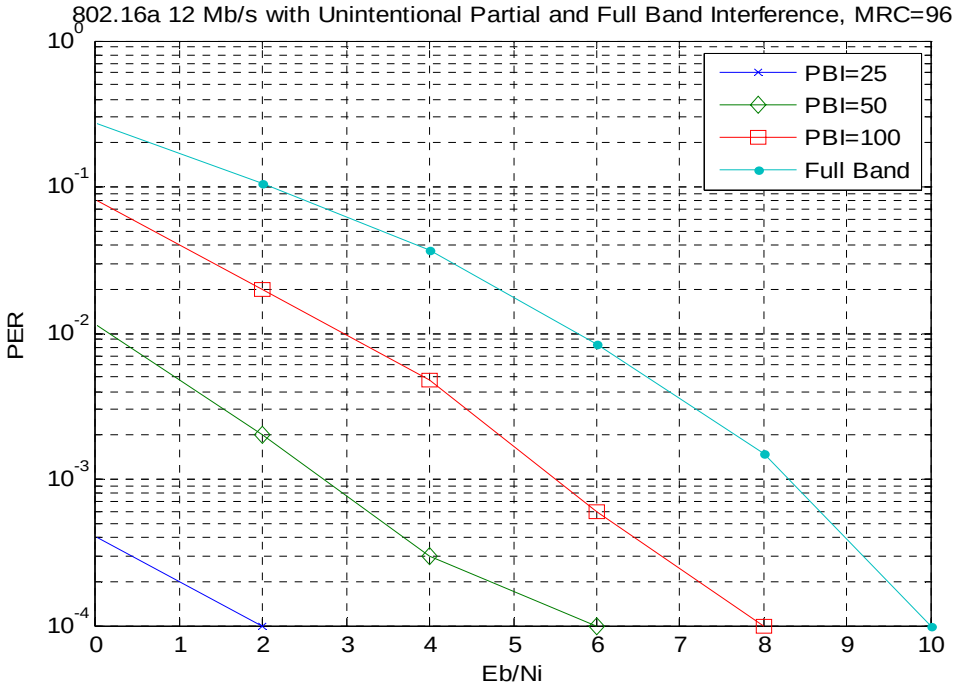

Figure 50 12 Mb/s, MRC =96, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

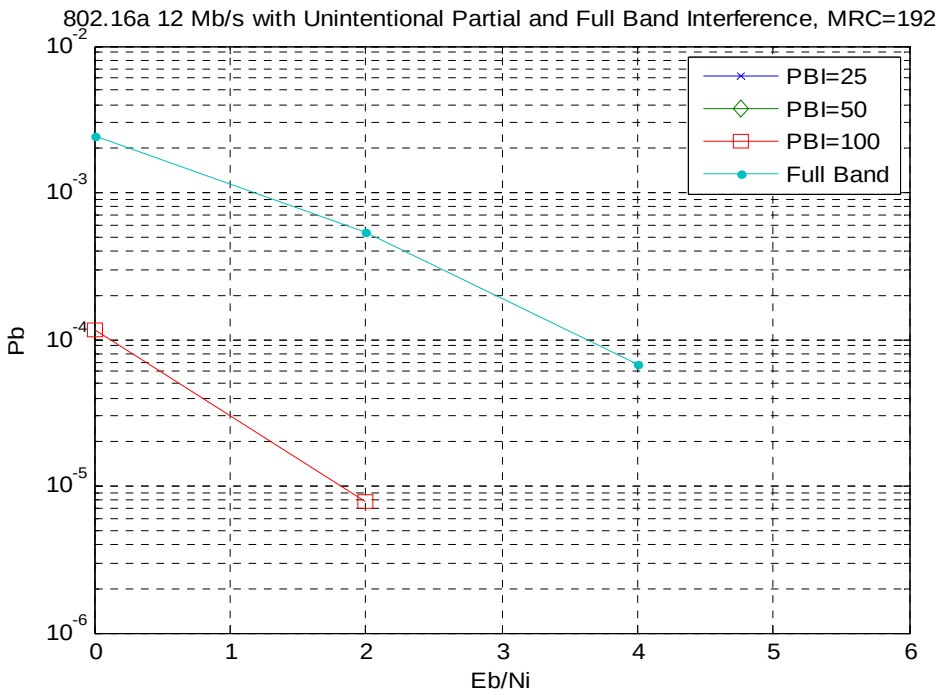

Figure 51 12 Mb/s, MRC =192, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

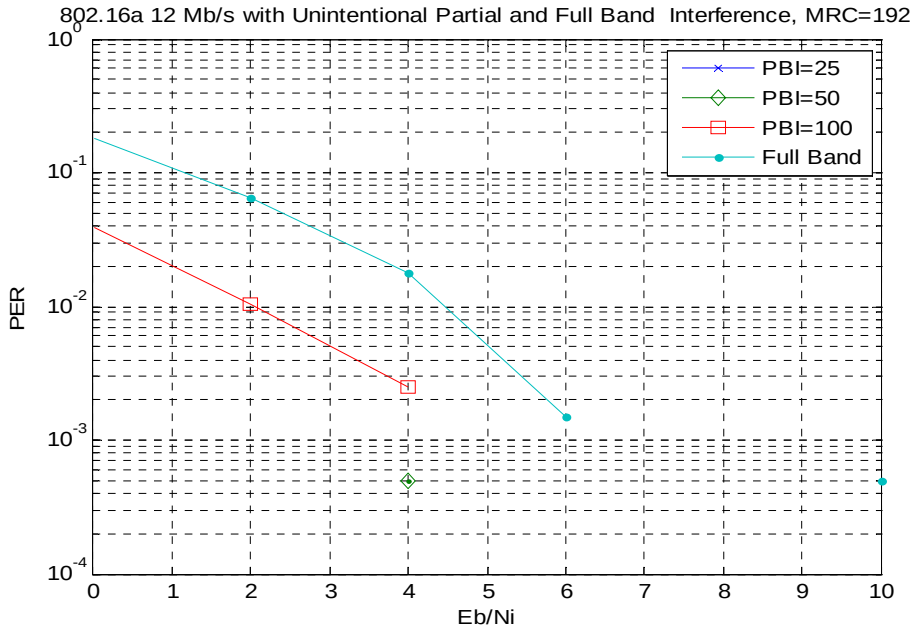

Figure 52 12 Mb/s, MRC =192, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is number of interference-corrupted subcarriers.

Figures 45 and 46 are essentially repeated from Figure 9 and Figure 10. They are repeated for easier comparisons between the no repetition case, which they represent, and the repetition cases in section 3. Figure 51 and Figure 52 list four data sets in the legend yet there are only two lines present, the lines for the two worst cases in terms of reliability, PBI = 100 and PBI = 200. The reason only two lines can be seen is that with the most reliable data rate of 12 Mb/s and L = 192, the data is going to be very reliable and for less than PBI = 100, there were no errors. If there are no errors, the data points do not plot.

4. 12 Mb/s, Constant PBI with Unintentional Interference

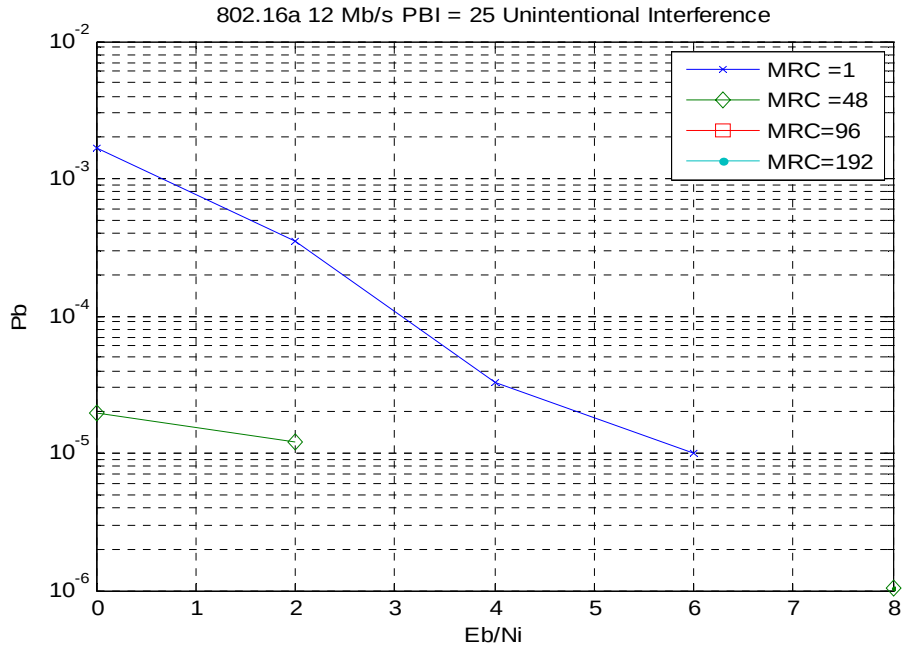

Figure 53 12 Mb/s, PBI=25, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

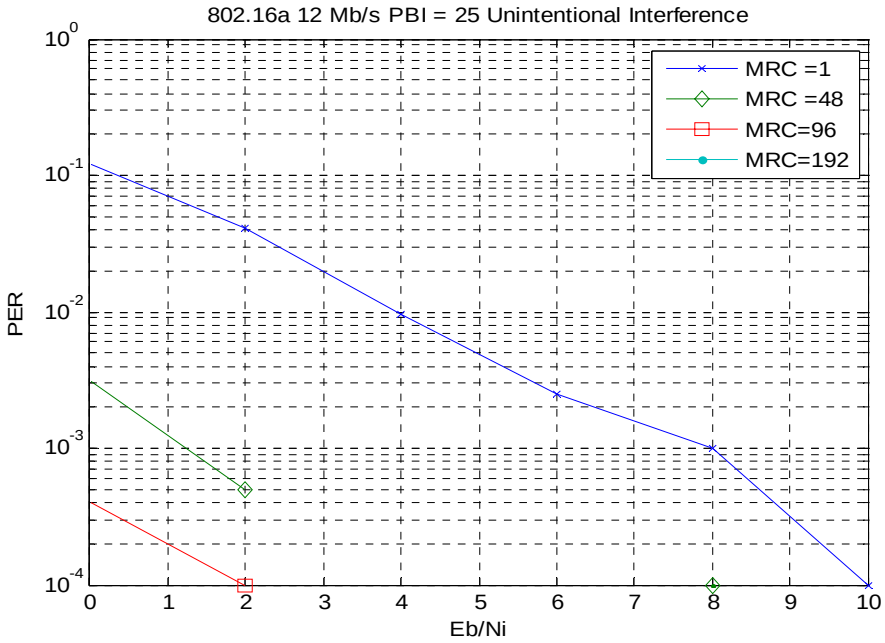

Figure 54 12 Mb/s, PBI=25, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

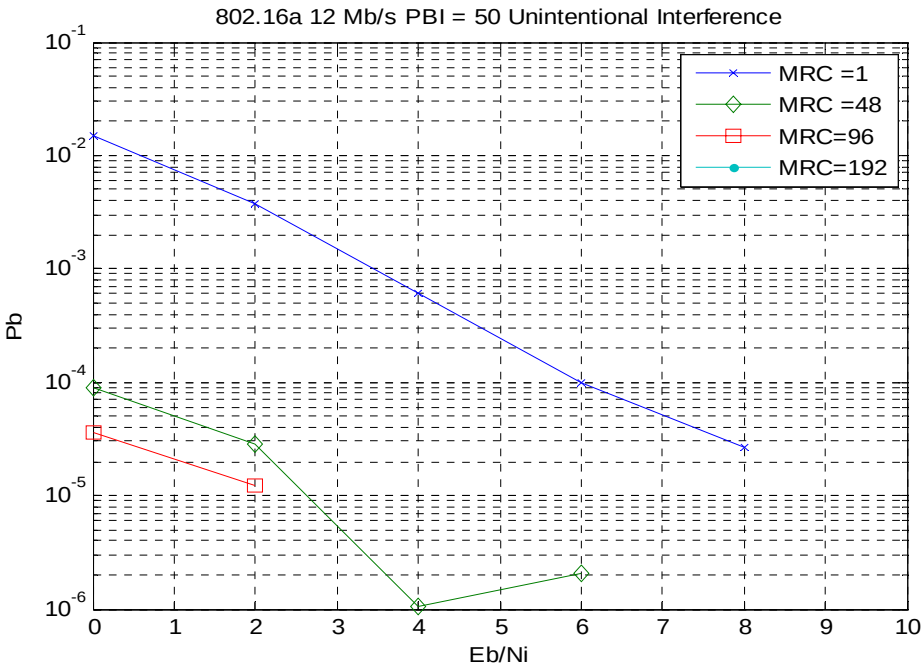

Figure 55 12 Mb/s, PBI=50, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

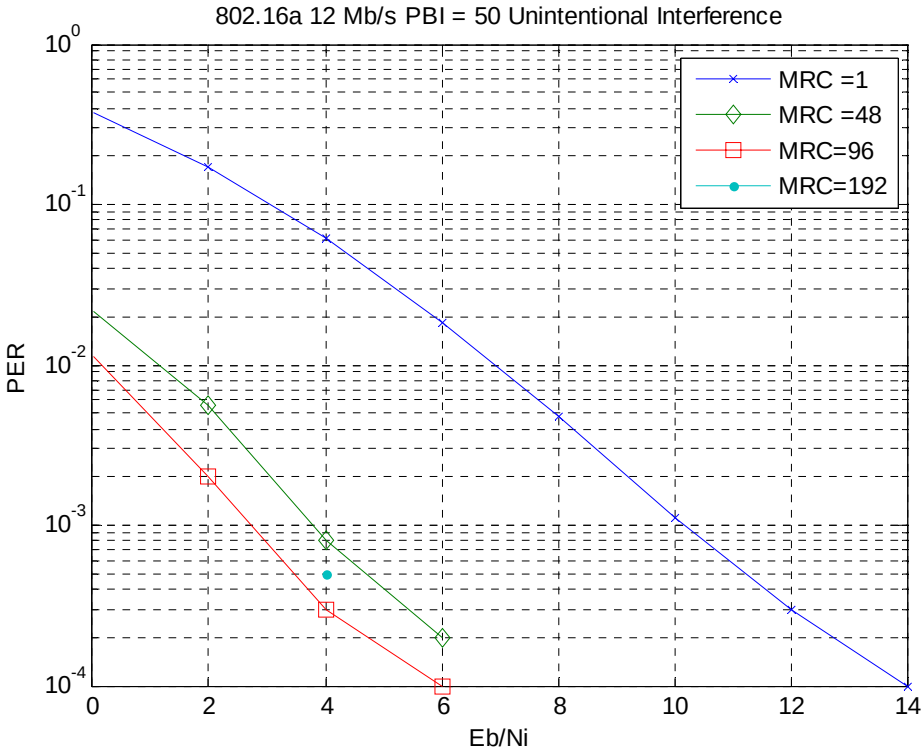

Figure 56 12 Mb/s, PBI=50, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

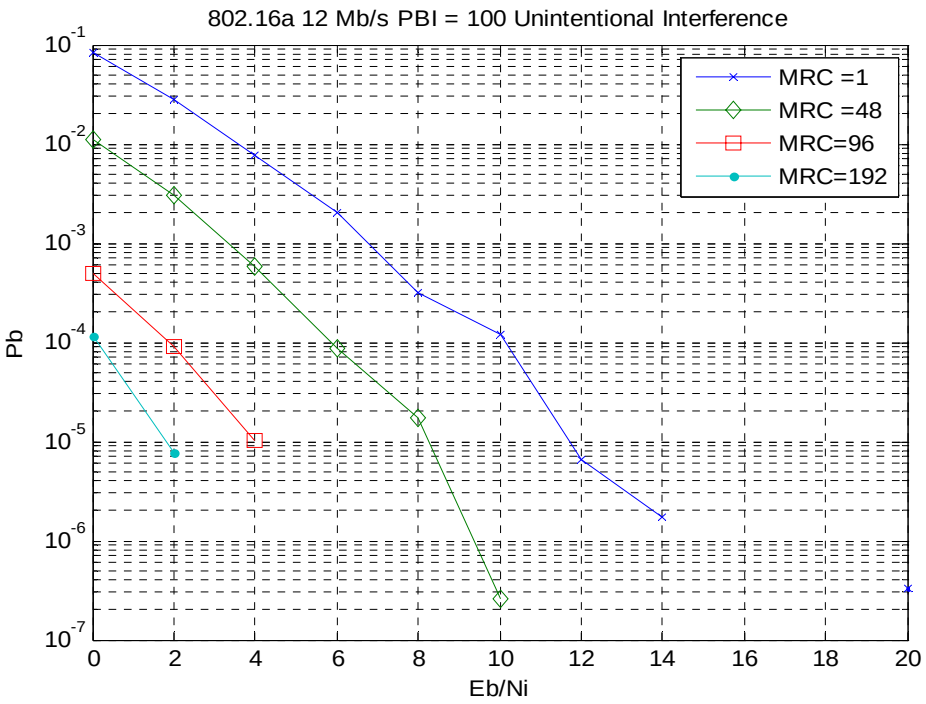

Figure 57 12 Mb/s, PBI=100, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

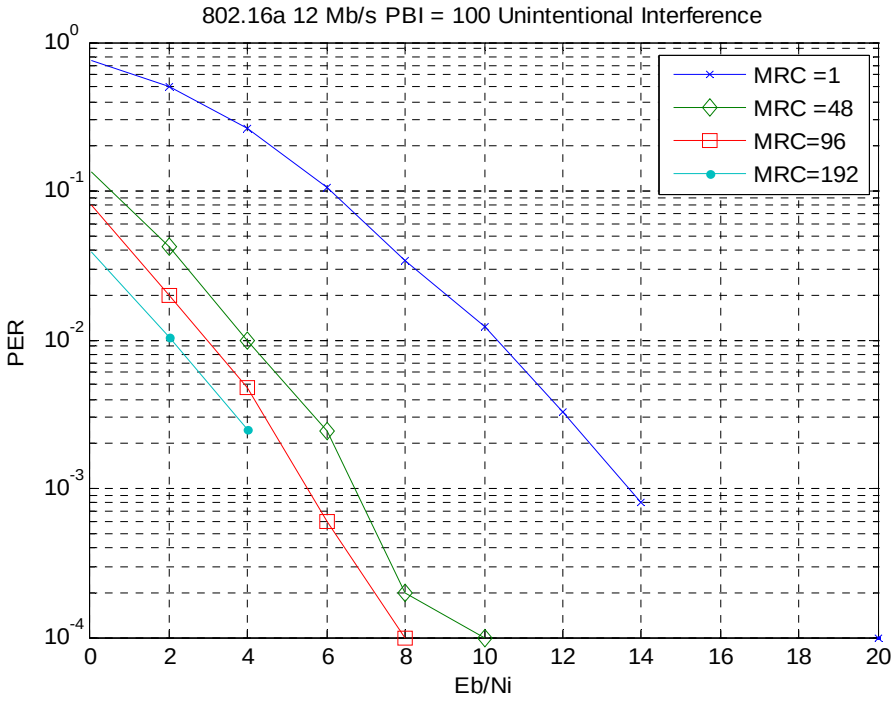

Figure 58 12 Mb/s, PBI=100, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

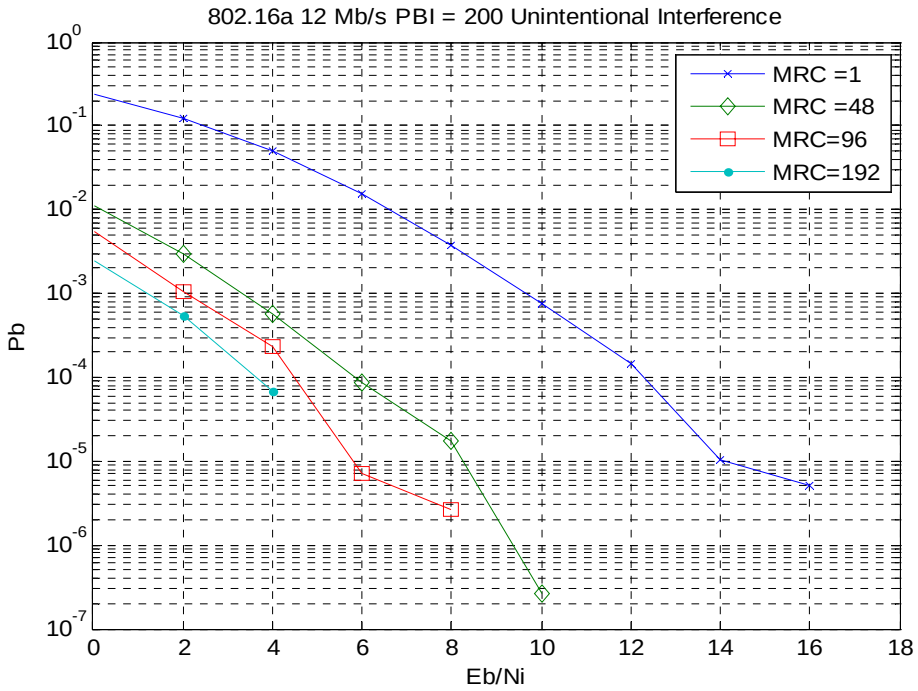

Figure 59 12 Mb/s, PBI=200, Probability of bit error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

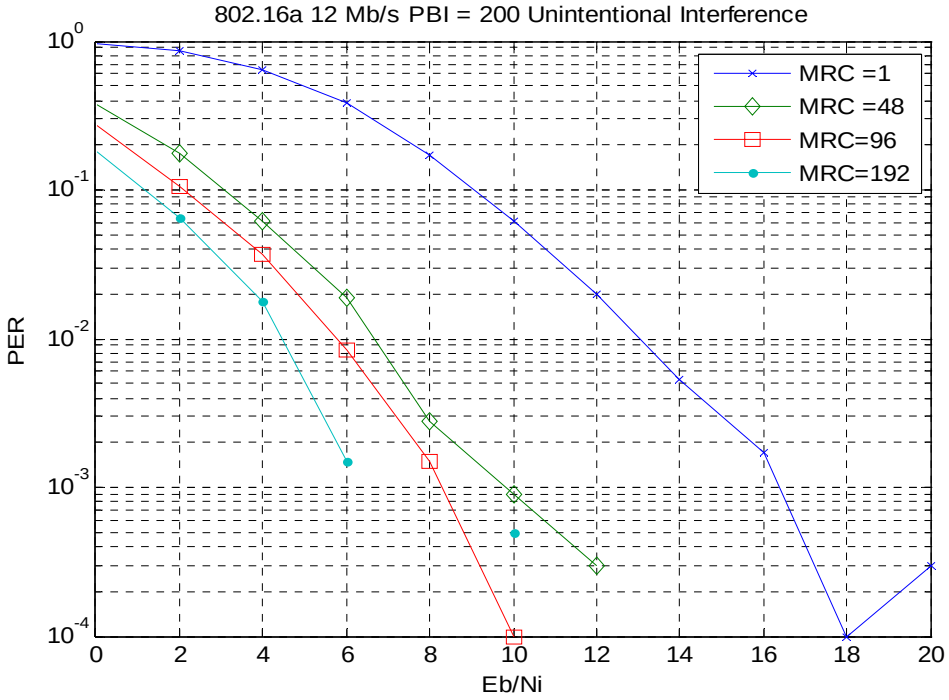

Figure 60 12 Mb/s, PBI=200, Probability of packet error vs. E_b / N_i with $E_b / N_o = 20dB$ in the presence of interference. Parameter is amount of repetition.

As with the data collected using 54 Mb/s, Figure 45 through Figure 60 show that using MRC results in a significant improvement in the performance but at the cost of data throughput. This result confirms the expectations that while MRC will reduce data throughput, it will significantly enhance performance. Using 54 Mb/s, MRC = 96, SNR = 20dB and PBI = 100, a SIR = 12 dB is required to achieve a $P_b = 10^{-4}$. Keeping all parameters the same except utilizing 12 Mb/s, only SIR = 2 dB is required to achieve the same $P_b = 10^{-4}$. Reducing the data rate offers a 10 dB performance gain. A more extreme example shows the additional utility MRC offers the user. To transmit with the absolute highest throughput the user can select 54 Mb/s with no MRC. In order to achieve a $P_b = 10^{-1}$, a SNR = 17 dB is required. Without MRC, the user could lower the data rate to 12 Mb/s to achieve $P_b = 10^{-1}$ with an SNR = 2 dB. However, by utilizing MRC = 48 and data rate 54 Mb/s, only SNR = 2dB is needed to achieve $P_b = 10^{-1}$. With the same data rate and MRC = 192, SNR = 0 dB achieves $P_b = 10^{-1}$. The performance gain from no MRC to MRC = 48 is the most significant gain.

Figures 53 through Figure 56 do not show all the curves listed in the legend because in certain cases in those figures the simulation yielded no bit errors and therefore approximated P_b and PER as zero. This falls in line with what would be expected. 12 Mb/s is the most reliable data rate and so it stands to reason that for MRC =192, P_b is approximately zero for both PBI = 25 and PBI = 50.

The research presented in this chapter found that using diversity and MRC drastically enhances the performance of 802.16a. Additionally, it was found that the most important factor is the amount of interference power not the number of interference-corrupted subcarriers. Also, decreasing the required E_b / N_i implies increasing the usable range meaning that performance can be traded for range. The next chapter provides a conclusion to the study as well as ideas for future work.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

A. SUMMARY

802.16a is an IEEE Wireless MAN standard that will likely be used across the world. Its low infrastructure requirements, high reliability and data rate and the commercial applications of 'WiMax' will keep 802.16a expanding. It is reasonable to consider the standard for military use because of its high performance with low power and its low cost with respect to most military radios, despite its requirement to have fixed BSs and SSs.

The system demonstrated the significant improvements in range, reliability or power can be achieved using MRC with 802.16a's OFDM mode. The cases that were investigated are unintentional interference, intentional interference and partial band jamming. With the 54 Mb/s data rate, improvements to the P_b and PER were between 13-15 dB depending on the MRC and PBI. With 12 Mb/s, only an 8 dB improvement was achieved to the P_b and the PER using MRC. Additionally, with MRC it was found that there was no advantage to an intentional interferer over an unintentional interferer from the jammer's perspective because it is the total amount of power that is the most significant factor, not how the power is distributed in frequency.

B. FUTURE WORK

This thesis investigated only a very small part of the broad standard of 802.16a leaving many possibilities yet to be explored in future work. One area which could be examined is a comparison of the effect of a multiple antenna system versus the effect of the MRC technique discussed in this thesis. Multiple antenna systems can lead to large diversity gains and could prove very useful for operation in the harshest interference channels. [6]

Lastly, the effects of MRC could be applied to IEEE 802.16e to accommodate mobile SSs. The 802.16e standard will likely provide the most use for the military as often times in the battlefield either the BS or the SS is mobile. MRC could enhance the performance of a potentially critical standard.

LIST OF REFERENCES

[1] IEEE 802.16a - 2003, "Air Interface for Fixed Broadband Wireless Access Systems-Amendment2: Medium Access Control Modifications and Additional Physical Layer Specifications for 2-11 GHz," IEEE Std 802.16a-2003.

[2] S. Smith, "Performance Analysis of Embedded 802.16a," Master's Thesis, Naval Postgraduate School, Monterey, CA, December 2006.

[3] M. Herlands, "Using Maximal Ratio Combining to Improve Performance of an OFDM Wireless LAN," Master's Thesis, Naval Postgraduate School, Monterey, CA, March 2007.

[4] Wikipedia, "IEEE 802.16," February 2007. http://en.wikipedia.org/wiki/IEEE 802.16 (last accessed April 2007).

[5] J. Allen, "Performance Analysis of 802.16a." Master's Thesis, Naval Postgraduate School, Monterey, CA June 2005.

[6] "IEEE 802.16 Task Groups and Committees," http:///www.ieee802.org/16/tgs.html. (Last accessed May 2007).

[7] T. Cooklev, *IEEE Wireless Communications Standards*; A Study of 802.11, 802.15, 802.16, IEEE Press, 2004.

[8] IEEE 802.16 Broadband Wireless Access Working Group, "Channel Models for Fixed Wireless Applications," July 2001. http://grouper.ieee.org/groups/802/16/tg3/contrib/802163c-01_29r4.pdf (last accessed October 2006.)

[9] "Definition: channelization," http://www.its.bldrdoc.gov/fs-1037/dir-007/_0929.htm August 23, 1996. (last accessed June 2007).

[10] Worldwide Interoperability For Microwave Access Forum, "Igniting Broadband Wireless Access," http://www.wimaxforum.org/news/downloads/WiMAXWhitepaper.pdf (Last accessed April 2007.)

[11] T. S. Rappaport, Wireless *Communications: Principles and Practice*, 2nd ed., Prentice Hall, Upper Saddle River, NJ, 2002.

[12] M. Sekgos, "Advanced Techniques to Improve the Performance of OFDM Wireless LAN," Master's Thesis, Naval Postgraduate School, Monterey, CA, June 2004.

[13] B. Sklar, *Digital Communications: Fundamental and Applications*, 2nd ed., Prentice Hall, Upper Saddle River, NJ, 2001.

[14] 14 IEEE 802.16 Broadband Wireless Access Working Group, "Channel Models for Fixed Wireless Applications," July 2001. http://grouper.ieee.org/groups/802/16/tg3/contrib/802163c-01_29r4.pdf (last accessed October 2006.)

[15] 15 J. G. Proakis, *Digital Communications*, 4th ed, McGraw Hill, New York, 2001.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Chairman, Department of Electrical and Computer Engineering, Code EC
   Naval Postgraduate School
   Monterey, California

4. Professor Tri T. Ha, Code EC/Ha
   Department of Electrical and Computer Engineering
   Naval Postgraduate School
   Monterey, California

5. Professor Frank Kragh, Code EC/Kh
   Department of Electrical and Computer Engineering
   Naval Postgraduate School
   Monterey, California

6. Donna Miller, Code EC/M
   Department of Electrical and Computer Engineering
   Naval Postgraduate School
   Monterey, California